1954

The effect of a hydrofoil at the stern of a destroyer type vessel upon its performance in still water

Vennig, Elias
Massachusetts Institute of Technology

THE EFFECT OF A HYDROFOIL AT THE STERN OF A DESTROYER TYPE VESSEL UPON ITS PERFORMANCE IN STILL WATER

Elias Venning, Jr.

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by

ELIAS VENNING, JR.

Lieutenant (junior grade), U.S. Navy

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SUBMITTED IN PARTIAL FULFILLMENT OF

FOR THE DEGREE OF

NAVAL ENGINEER

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1954

Cambridge, Massachusetts
24 May 1954

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

I herewith submit the attached thesis entitled THE EFFECT OF A HYDROFOIL AT THE STERN OF A DESTROYER TYPE VESSEL UPON ITS PERFORMANCE IN STILL WATER in partial fulfillment of the requirements for the degree of Naval Engineer.

Respectfully submitted,

Elias Venning, Jr.

THE EFFECT OF A HYDROFOIL AT THE STERN OF A DESTROYER TYPE VESSEL UPON ITS PERFORMANCE IN STILL WATER, by Elias Venning, Jr. Lieutenant (junior grade), U.S. Navy. Submitted in Partial Fulfillment of the Requirements for the Degree of Naval Engineer, Department of Naval Architecture and Marine Engineering, May 24, 1954.

ABSTRACT

The object of this work was to investigate the effects of a hydrofoil located at the stern of a high-speed surface vessel. Damping out of the first hump in the stern wave train of the vessel appears to be possible by the use of a properly positioned hydrofoil having correct dimensions. Hence, in particular, this thesis was directed toward establishing the effects on total resistance coefficient which resulted from varying hydrofoil chord length, longitutinal position, angle of attack, and depth of submergence.

The vessel tested with stern hydrofoils was a model of a fine-lined, transom-stern, destroyer type ship. To this model were attached hydrofoils whose basic shape corresponded to N.A.C.A. Foil No. 63_3-618. The chord length of this standard shape was varied so as to produce a family of five similar hydrofoils. For each of these hydrofoils the optimum longitudinal position and angle of attack was determined. For the smallest chord length hydrofoil the effect of depth of submergence was evaluated. Finally, with each foil at its optimum position, the effect on the model's total resistance coefficient was established.

As an indication of the results to be achieved with bow hydrofoils on this particular vessel, the final stages of the investigation were devoted to determining the proper position for a bow hydrofoil. The effects produced by locating the hydrofoil at that position were then evaluated.

It was found that for the particular vessel under consideration no reduction in total resistance coefficient by use of stern hydrofoils was possible. Additionally, it further appeared that bow hydrofoils would cause no improvement in total resistance characteristics for this vessel.

The presence of stern hydrofoils of varying chord length was consistently deleterious, hence the apparent optimum position and chord length were optimum only in that they caused the least increase in total resistance coefficient. The optimum (LBP)/(chord length) ratio was found to be 25.99. The optimum longitudinal position was 1.0115 x (LBP) aft of the forward perpendicular. The optimum (cut away angle)/(angle of attack) ratio was (-) 13. The optimum depth of submergence was one chord length.

The conclusion drawn from this work is that the application of stern hydrofoils to very fine-lined hull forms will result in no reduction of stern wave making resistance. Additionally, the presence of a bow hydrofoil beneath a bulbous type bow appears to result in no reduction of bow wave making resistance for the hull form that was investigated.

In order to verify the conclusion reached as to the effect of hull form on the results caused by stern hydrofoils, it is recommended that a full-bodied model having the same displacement and wetted surface as that tested in this thesis be built. Then, to this new model apply the same family of stern hydrofoils in order to determine if a beneficial result can be achieved on fuller hull forms.

Thesis Supervisor: Martin A. Abkowitz

Title: Assistant Professor of Naval Architecture

The purpose of stern hydrofoils of varying chord length was [illegible], [illegible] the optimum [illegible] position and chord length were [illegible] only in that they exhibit the least increase in total resistance coefficient. The optimum (chord/(model length)) ratio was found to be [illegible]. The optimum longitudinal position was [illegible] aft of the forward perpendicular. The optimum (last away angle/(angle of attack)) ratio was (-) [illegible]. The optimum depth of submergence was one chord length.

The conclusion drawn from this work is that the application of stern hydrofoils to very fine-lined hull forms will result in no reduction of calm water resistance. Additionally, the presence of a bow hydrofoil [illegible] a [illegible] type bow appears to result in no reduction of calm water resistance for the hull form that was investigated.

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ACKNOWLEDGMENT

It is not possible to give adequate, explicit credit to all those individuals who have directly and indirectly given aid in the development of this thesis. However, the writer is deeply grateful to all of them for their help, and wishes to acknowledge his debt to them.

His greatest debt is to Professor Martin A. Abkowitz, who gave unceasing assistance and encouragement during the conduct of the thesis. In fact, the original idea to employ stern hydrofoils as wave reducing devices was that of Professor Abkowitz. For the timely advice and continuous help given him by this gentleman, he expresses his most sincere thanks.

Special acknowledgment is also due to Mr. N.L. Ficken, Jr. and Mr. J. R. Paulling, Jr., of the staff of the Department of Naval Architecture and Marine Engineering at the Massachusetts Institute of Technology, for their assistance in connection with the experimental and photographic work at the Towing Tank. Their experience greatly assisted the author in the techniques employed to obtain reliable data.

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Finally, to Mrs. V.A. Manganelli for her untiring secretarial help, the author extends his appreciation.

Cambridge, Mass.
May, 1954

Elias Venning, Jr.

NOMENCLATURE

Symbol	Description	Units
R_T	Total Resistance	Lbs.
C_T	Total Resistance Coefficient	---
C_F	Frictional Resistance Coefficient	---
LBP	Length Between Perpendiculars	Ft.
S	Wetted Surface	$Ft.^2$
V	Speed or	Ft./sec. Knots
ρ	Density of Water	$Lb.sec^2/Ft^4$
ν	Kinematic Viscosity of Water	Ft^2/sec
l	Longitudinal Position of Foil	Ft.
F.A.P.	Forward of After Perpendicular	---
A.A.P.	Aft of After Perpendicular	---
F.F.P.	Forward of Forward Perpendicular	---
A.F.P.	Aft of Forward Perpendicular	---
h	Hydrofoil Depth of Submergence	Inches
α	Hydrofoil Angle of Attack (relative to the horizontal)	Degrees
N.A.C.A.	National Advisory Committee on Aeronautics	---
c	Hydrofoil Chord Length	Inches

Symbol	Description	Units
C_L	Coefficient of Lift	---
C_D	Coefficient of Drag	---

CONTENTS

CONTENTS (continued)

I. INTRODUCTION

Background Theory

1. Resistance Theory.

Any body moving through water will encounter a resistance to its motion. In the case of a body only partially submerged in water, this resistance is made up of three components which are:

1. Frictional resistance
2. Eddy or form resistance.
3. Wave making resistance.

Frictional resistance is a function of the viscosity of the medium, while the wave making resistance is independent of viscosity. Eddy or form resistance was long considered to be independent of viscosity also; however, present-day investigators(1) have established that the form resistance should properly be grouped with the frictional resistance, since they are both dependent on the viscosity of the water. Therefore, they are functions of Reynolds' number, while the wave making resistance is considered to be a function of Froude's

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number, $V/\sqrt{gL}$. Now a consideration of the resistance characteristics of ship-shaped bodies in general indicates that at low values of Froude's number $V/\sqrt{gL}$, or speed-length ratio $V/\sqrt{L}$, the major percentage of a vessel's total resistance is due to friction. However, when the value of the speed-length ratio increases to unity and greater, the wave making resistance shows a sharp increase while the frictional resistance tends to decrease. This increase in wave making resistance at the high speed-length ratios is of considerable significance, for it represents an ever increasing power that must be built into any ship that will be driven at high speeds. Quite obviously, it would be to the designer's advantage if he could achieve a reduction in this high speed wave making resistance by some means which were less costly than the propulsion equipment necessary to achieve the added high speed. With this thought in mind, it then follows that it might be possible to employ some device which would reduce the wave making resistance to a degree significantly greater than the expected increase in the frictional and eddy resistances due to the device.

2. Ship Wave Characteristics

The fact that ships do create waves as they move

through water is universally realized, but what is not so widely known is the fact that these waves are really the resultant of two families of waves. The bow and stern of any ship underway are traveling disturbances, and as such they each cause to be formed a wave family which consists of a diverging system and a transverse system. (See Fig. I.) To Lord Kelvin credit is given for a mathematical solution which defines this transverse-diverging wave group in terms of an ideal problem. There are some variations from actuality in the classic Kelvin solution, but these are to be expected since Kelvin considers the disturbance as being due to forces at one single point, whereas for a ship the disturbing forces are spread over the hull. It is to be noted that these two families of waves will change their basic properties of amplitude and wave length as the speed of the ship varies. As the speed increases, the transverse components of each family tend to increase in wave length.

Now in examination of wave making resistance versus speed-length ratio curves, it is customary to find that these curves are characterized by distinct hollows and humps. These hollows and humps are explained by the fact that the bow and stern transverse waves have come into coincidence either in phase so as to result in more

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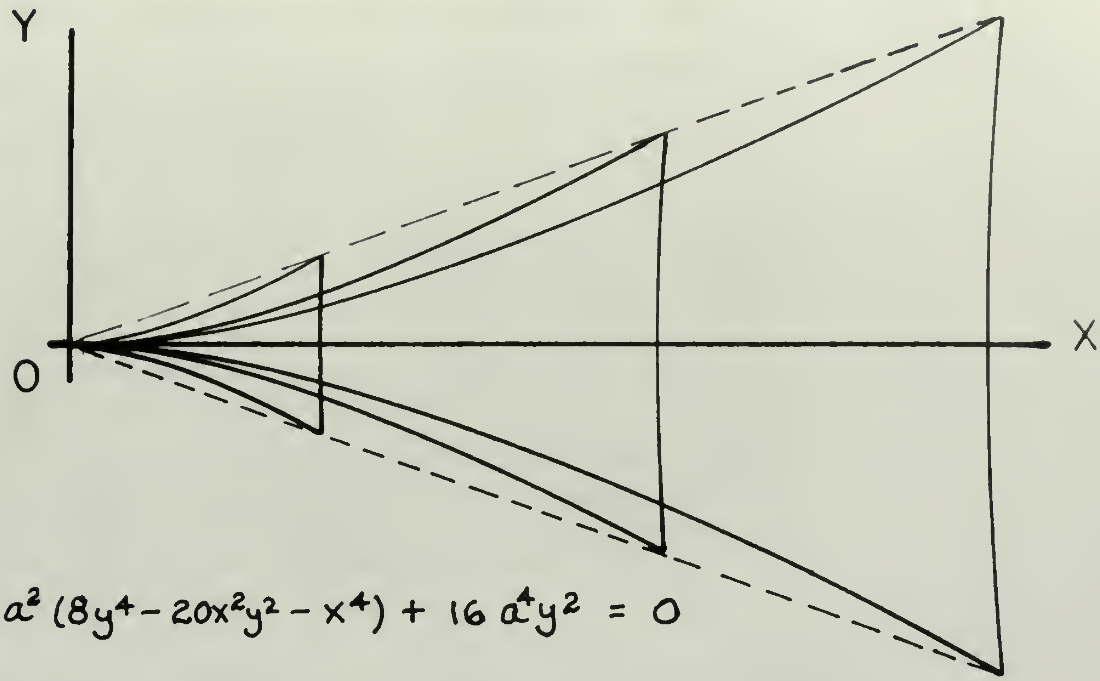
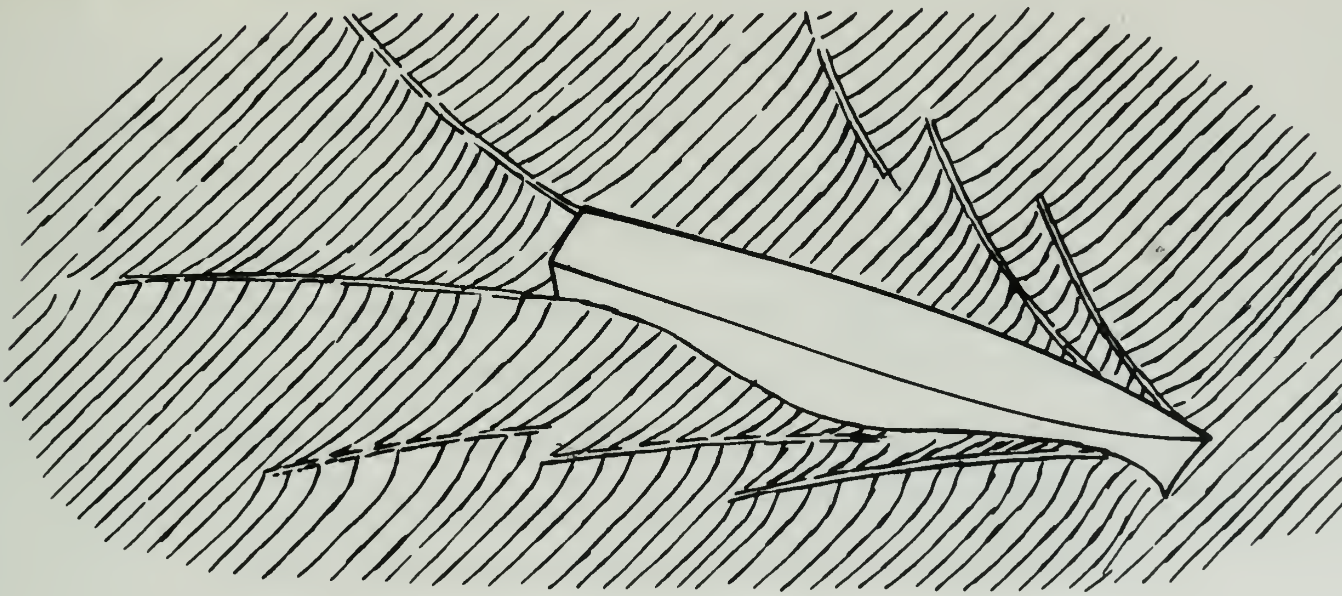
FIGURE I.

KELVIN WAVE GROUP & SHIP WAVE TRAINS



$$(x^2+y^2)^3 + a^2(8y^4-20x^2y^2-x^4)+16a^4y^2 = 0$$

CRESTS OF A KELVIN WAVE GROUP CAUSED BY A TRAVELLING DISTURBANCE AT O.



BOW AND STERN WAVE SYSTEMS SHOWING DIVERGENT AND TRANSVERSE CREST GROUPS.

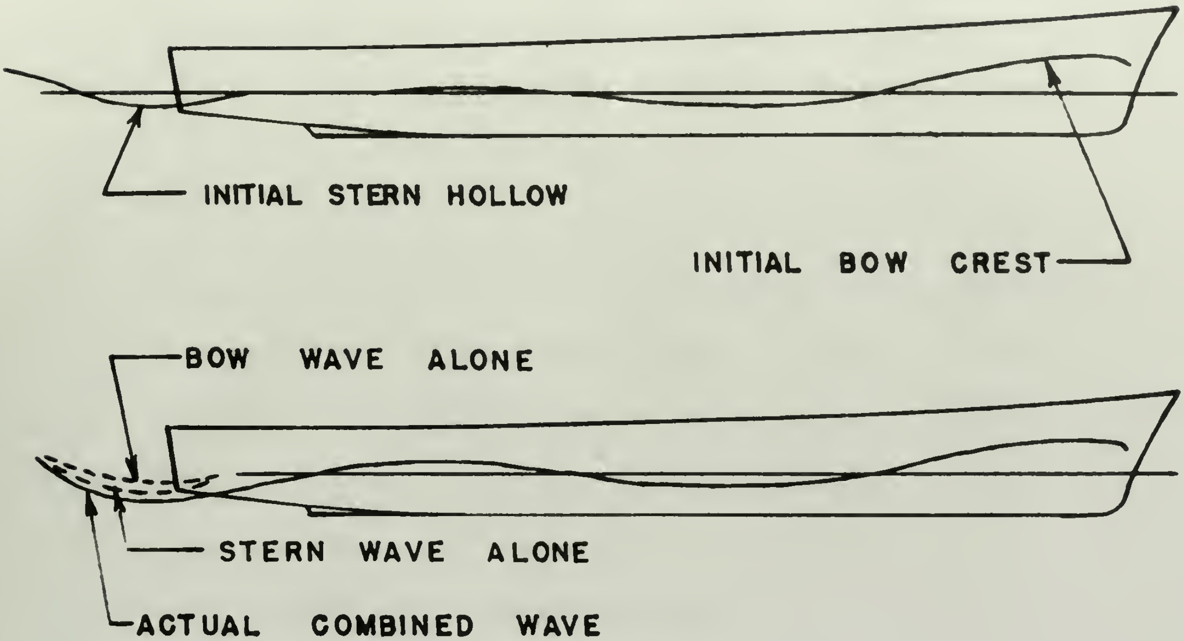
resistance (hence a hump), or out of phase so as to result in less resistance (hence a hollow). Perhaps this phenomena is better explained by quoting the words of Prof. K.S.M. Davidson[2]:

> ".... Now the residual resistance is simply the excess of the sum of the aftward-acting components of the normal pressure forces on the fore body over the sum of the forward acting components on the after body. The pressures themselves tend to be high when the surface levels are high, and low when the surface levels are low. Thus the humps and hollows are accounted for, qualitatively, by the effect of the wave train initiated at the bow on the surface levels around the stern." (See Fig. II.)

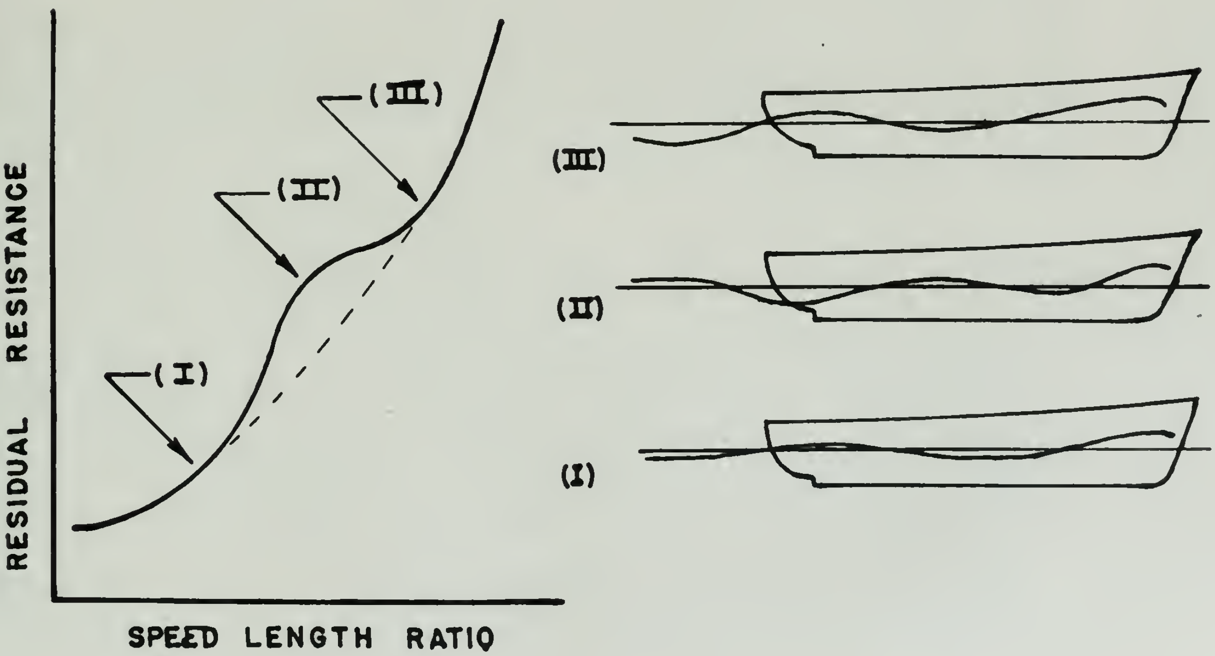
From the standpoint of reduction of wave making resistance, the essence of what has just been stated is this: if a secondary wave system is imposed upon a primary system so that the two systems are out of phase by 180 degrees, there will be a reduction in the amplitude of the primary system. This reduction can theoretically be a complete reduction to a zero level of disturbance if the amplitude of the secondary system and its other wave characteristics are the same as those of the primary. Assuming that the primary system can be reduced or eliminated by some device, it would appear that a reduction in wave making resistance would result. But now, the problem has been simplified to that of finding a device which is capable of producing a con-

FIGURE II.

BOW-STERN WAVE INTERFERENCE



IIA. EFFECTS OF BOW & STERN WAVE COINCIDENCE.



IIB. CORRELATION BETWEEN WAVE PROFILES & SHAPE OF RESIDUAL RESISTANCE CURVE.

trollable secondary wave disturbance. Such a device might possibly be a hydrofoil, and so let us examine the properties of a hydrofoil.

3. <u>Properties of a Hydrofoil</u>

In addition to the lift and drag characteristics possessed by these underwater wings, or hydrofoils, there is a third characteristic of particular note. Hydrofoils will cause a wave-like disturbance to be set up on the free surface of the water. Keldysch and Lavrentiev(3)(4) in 1934 arrived at a two-dimensional treatment of the problem in which they considered the hydrofoil as being a bound vortex. They proposed the following expression which indicated the wave ordinate, y, that exists at a distance x aft of the bound vortex (whose strength is Γ) when the vortex is at submergence h in a free stream velocity of V fps:

$$y = \frac{-2\Gamma}{V} \left[e^{-\frac{1}{\frac{V^2}{gh}}} \right] \sin \frac{gx}{V^2} \qquad (1)$$

In practice, this has been found to be a good approximation to the surface for distances of one-quarter wave length or more behind the foil(3). The fact that it is an approximation though is easily understood, for when we consider the hydrofoil from a three-dimensional

standpoint we necessarily introduce the effects of trailing vortices. These vortices will produce transverse waves which are noted by the presence of "roostertails" in the wake of the foil.

Now, returning to our original proposal to employ some device which would be able to lessen wavemaking resistance, it would appear that a properly positioned hydrofoil adjusted so that it produced high circulation, Γ, would be an answer to this quest. Accordingly, what has been described before in this Introduction will now serve to explain the reasons behind the investigations and proposals that will next be mentioned.

Chronological Background of M.I.T. Hydrofoil Investigations

This thesis is essentially one more step in a series of investigations at the M.I.T. Ship Model Towing Tank into the use of properly placed hydrofoils as wavemaking reduction devices.[5]

The first investigations were conducted by J.R. Paulling, Jr.[6] and Henry Kozlowski[7] in 1952. In the subsequent year of 1953, A.L. Beal and Abraham Zakay[8] continued Mr. Paulling's investigations. Also in 1953, C.E. Jones and W.H. Brooks[9] carried out an investigation to determine the nature of the surface waves generated by submerged hydrofoils.

Messrs. Paulling, Beal, and Zakay have shown that a reduction in wavemaking resistance can be achieved by the use of bow hydrofoils of proper design. Mr. Kozlowski in the final stages of his investigative work obtained results that indicated that horizontally placed stern hydrofoils also could bring about a reduction in wave making resistance.

Intentions of This Investigation

This investigation serves to continue Mr. Kozlowki's work with a more detailed analysis of stern hydrofoils. In particular it was decided that the effects of varying the hydrofoil chord length, angle of attack, depth of submergence and fore-and-aft position would be investigated. In order to shorten the testing schedule so that it could be completed in the available time, it was further decided to investigate the effects of the stern hydrofoil at only two ship-speed ranges, namely, 15 knots and 32 knots. These, of course, were the most significant speeds since they represented the cruising and full power speeds of the actual vessel. If a significant reduction in wave making resistance could be achieved in either or both of these ranges, then there would be justification for consideration of the hydrofoil's effect over the entire speed range. With these thoughts in mind, let us

next consider the equipment that was employed in this investigation.

Description of Equipment

1. Ship Model

The selection of the model to be tested required that careful attention be paid to the limitations on model size brought about by the physical dimensions of the M.I.T. Towing Tank, which was to be the location of testing. Mr. Kozlowski in his work had employed a model of a destroyer type vessel whose length was 5.5 feet. In order to reach the designed 1.82 speed-length ratio of the ship, he found it necessary to drive the model to a speed of 4.26 knots. At this high speed he found that the model was very liable to yaw, and that the runs were of such short duration that many runs had to be repeated in order to be certain of the reliability of the readings.

It was therefore clear that a smaller model than that employed by Mr. Kozlowski was needed. Accordingly, arrangements were made with the David W. Taylor Model Basin for the loan of a suitable model. The model received was that of a fine lined, transom-stern, anti-submarine-warfare type vessel. The designed speed

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It was therefore clear that a smaller model than that employed by Mr. Kaltenski was needed. Accordingly, arrangements were made with the David W. Taylor Model Basin for the loan of a suitable model. The model received was that of a twin screw, transom-stern, [illegible] type vessel. The designed speed

length ratio of the ship was 1.403 which necessitated driving the 4.333 ft. model to only a speed of 2.920 knots when considering the 32 knot speed range of the full size ship. Full details of this model will be found in Appendix A, and a photograph of it may be seen in Figure III.

2. <u>Model Towing Bracket</u>. (see Fig. IV.)

Upon receipt of the 4.333 foot model from the David Taylor Model Basin, it was clear that the very light weight of the model (7.63 pounds) and its very narrow beam (0.446') would possibly cause stability problems during towing. The conventional towing bracket used at the M.I.T. Towing Tank is designed for models of 25 pounds or more in weight. These heavier models make it quite acceptable to add a horizontal, hollow, aluminum bar at the upper ends of the towing arms, in which is carried a spring loaded mechanism for adjusting towing cable tension to five pounds. However, for this lighter 7.63 pound model it was indicated that a special lightweight towing bracket was necessary so as to guard against possible capsizing of the model.

The possibility of capsizing was due to the high weight of the tension adjusting rod, hence elimination of this danger called for elimination of the tension

FIGURE III

Model DTMB-DD 332

Note permanently installed level on forecastle, and plastic covering over open portions of hull.

FIGURE IV

Details of Balsa Towing Bracket

Note the heavy tension setting bar in the foreground. M.I.T. Towing Tank bracket is shown in the background. Contrast this with the balsa bracket in the middle which has a lower center of gravity.

adjusting device. It was with some misgivings that the decision to eliminate this device was made. The applied towing force for any given run must be corrected for the frictional resistance introduced by the dynamometer system. In order to evaluate the magnitude of this frictional resistance it is necessary to maintain a constant static tension in the towing cable. Of course, this tension could be varied, but it is the practice to maintain it at five pounds. The alternative that had to be accepted was to first set the towing cable tension at five pounds by means of the tension-setting spring-loaded aluminum bar which had been separated from its associated components. When this had been done, a length of very fine bronze wire of low ductility and low elasticity was passed in between the two ends of the towing cable (which were attached to the tension-setting device). This wire was then adjusted in length so that it exactly equalled the distance between the connecting points on the tension-setting device. Thereafter, the five pound pull was transferred to the bronze wire, the tension-setting device was slackened, and then finally removed.

As regards the actual towing arms, they were constructed of $\frac{1}{8}$-inch sheet balsa wood. They were similar to a T-type stiffener in cross section, and were attached to the model by means of aluminum bearing rings which

fitted over a plexiglass shaft. This shaft in turn was rigidly attached to the model by aluminum angle pieces. As can be inferred from this description, every effort was made to keep the towing bracket as light as possible, but still of adequate strength. Details of this arrangement may be seen most clearly in Figure IV.

3. <u>Hydrofoils</u>. (see Fig. V.)

In the original conception of this thesis it had been intended that before any attempts were made to select a suitable hydrofoil shape there would be a detailed photographic analysis made of the stern wave characteristics of the model. From this analysis it would have been possible to have determined the wave ordinates, y, that were to be cancelled by the secondary wave disturbance created by the submerged hydrofoil. Consideration of the Keldysch-Lavrentiev formula,

$$y = \frac{-2\Gamma}{V}\left[e^{-\frac{1}{\frac{V^2}{gh}}}\right] \sin\left[\frac{gx}{V^2}\right] \qquad (1)$$

will indicate that if we had such wave ordinates, we could substitute their values (with negative algebraic signs) into this formula. Then, for given x values and h values of the hydrofoil, and at a given speed range V, we could determine the necessary value of

FIGURE V

Family of N.A.C.A. 63_3-618 Hydrofoils

As used in this investigation. Note the unfinished, as-cut, 1.0 inch hydrofoil in the foreground.

circulation, Γ, that would have to exist to satisfy the equation.

Now for an air foil, or hydrofoil, the circulation around the foil is defined by:[10]

$$\Gamma = \tfrac{1}{2}\, C_L\, U_o\, c \qquad (2)$$

This expression indicates that for a given approach velocity, u_o, the produced circulation, Γ, is directly proportional to the coefficient of lift, C_L, and the foil chord length, c.

If circulation was the only characteristic affected by changes in the coefficient of lift and the chord length, the problem would be much simplified. However it must be realized that there are two additional foil characteristics that will be affected by any change in C_L or c. When C_L is increased, there is generally an increase in the coefficient of drag, C_D, of the foil. This infers an increased form resistance. Additionally, as the chord of the foil is increased, the wetted surface of the hydrofoil is increased, and this infers an increased frictional resistance. Hence discrimination must be exercised in a selection of C_L and c that are to produce the required circulation.

Now if it had been possible to photographically determine the wave ordinates, an analysis could have

been made to have determined the optimum values of C_L and c by the use of the Keldysch-Lavrentiev formula. However, other conditions forced this photographic analysis to be omitted. Originally, arrangements had been made with the Sloan Automotive Laboratory machine shop to machine cut the desired hydrofoils during the last part of March 1954. This schedule would have permitted a photographic analysis. Instead, the machine shop found that it was faced with a high priority block of machining work that would be at its peak just when the original schedule had called for the hydrofoils to be cut. Hence, the photographic analysis had to be omitted, for the sake of obtaining the services of the special foil cutting machine.

Lacking a photographic analysis, some other rational methods had to be devised so as to form a basis on which to determine the hydrofoil cross-section, span, chords, and tip shape.

The hydrofoil cross-section selected was based upon a careful consideration of the lift-drag characteristics of the many standard N.A.C.A. sections described in reference (11). What was most wanted in the foils considered was a high lift to drag ratio as the angle of attack of the foil increased. Approximately eight different foils were found to be outstanding in this

property and a selection of any one from among this group was based on very small differences that might easily be considered arbitrary. It is quite possible that the foil shape selected was not the best shape, and that some other shape might have been better, but it is believed that the differences would have been slight. N.A.C.A. section 63_3-618 was therefore selected for this investigation. A list of the other possible foils will be found in Appendix B.

The decision as to the span dimension of the foil was coerced by the need for control over the number of variables that were to be considered. Under the discussion devoted to Intentions of This Investigation it has already been mentioned that hydrofoil chord length, angle of attack, depth of submergence, and fore-and-aft position were the variables under consideration. It was felt that these were the most important variables and that span length should be kept constant at a value equal to that of the model's greatest beam, that is, 0.446 ft.

As regards chord lengths for the hydrofoil, it was the original intention in this investigation that a family of hydrofoils should be tested. This family was to be of the same basic shape (for example, N.A.C.A. 63_3-618) and was to have a constant span of 0.446 ft. However, the chord length was to be varied. Since

Mr. Kozlowski had employed a foil whose L.B.P./chord length ratio was 24 to 1, it was felt that a family of five foils which bracketed this ratio would give reasonable assurance of success. Accordingly, a family of foils having chords of 3 inches, 2.5 inches, 2 inches, 1.5 inches, and 1 inch was decided upon.

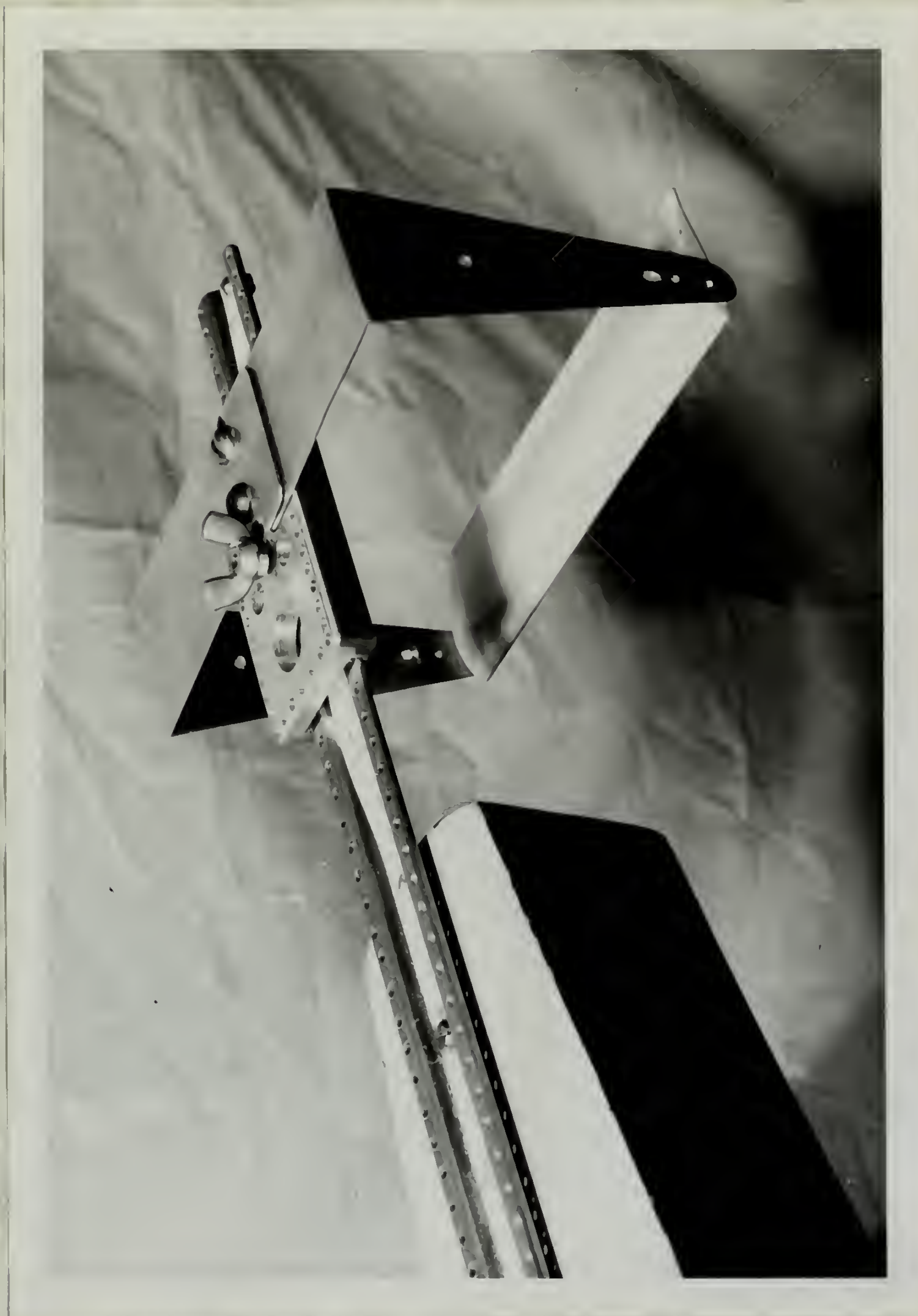
Before leaving the discussion of the hydrofoils it should be stated that it was purposely decided to leave the tip edges of the foils blunt and square. It was realized that additional form drag losses, as tip vortices, would result; however, the foils had been machine cut, and hence were as nearly similar as possible. Any tapering of the tips would have been done by hand, and since dissimilarity as well as danger of breakage would result, it was decided not to alter the tips. Additionally, the foils were cut from mahogany, and so a thinning of the tips would have increased the chances of warpage while the foils were submerged. In Appendix C will be found additional details on the N.A.C.A. 63_3-618 shape that was employed.

4. <u>Hydrofoil Support Device and Track</u>
(see Fig. VI.)

The design of the hydrofoil support device had to meet three requirements. It had to be of minimum weight, had to insure close positioning accuracy, and

FIGURE VI

Details of Stern Hydrofoil Support Device



Showing the 1.5 inch foil set at keel depth.

most of all, had to be simple in operation. These aims were quite well met in every respect. The support device was of aluminum and lightness was further achieved by liberal use of lightening holes. The positioning track upon which the support device rode was merely a piece of 1 inch wide sail track as used on sail boats. This piece of track was considerably lightened by removing the entire central web of the track with a milling machine. Additionally, the riding lips of the track were lightened by lightening holes.

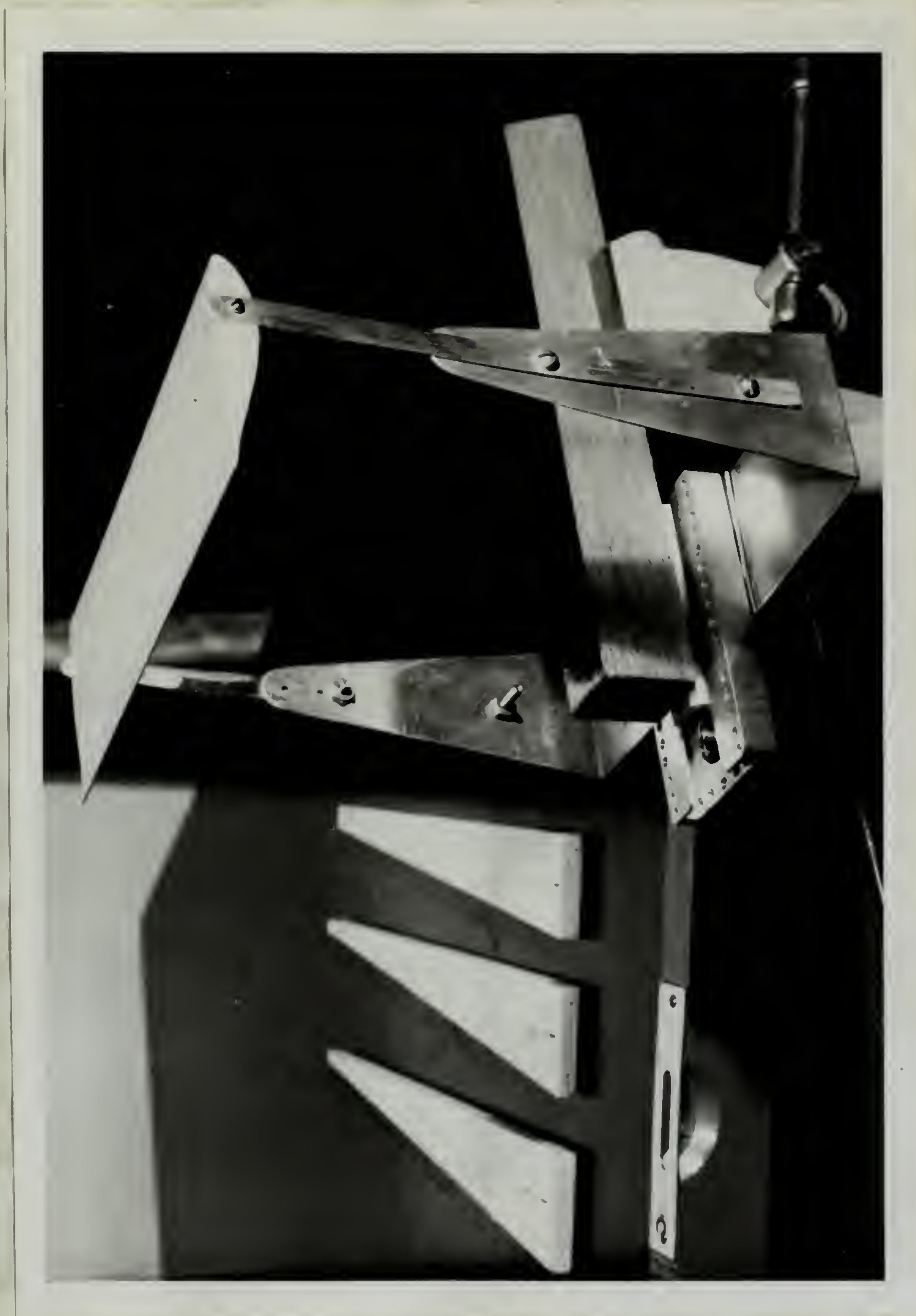
To facilitate the setting of the hydrofoil support device in different positions relative to the After Perpendicular of the model, a plastic strip of 1/16-inch thickness ruled off in 10ths of a foot was inserted between the lips of the positioning track. The rule's A.P. index, was offset three quarters of an inch aft of the A.P. so as to coincide with the index mark on the support device which was three quarters of an inch aft of the support point on the foil. Next, it should be mentioned that the foil support point was at a position on the foil mean line a distance of 25% of the chord aft of the leading edge. (see Appendix C).

5. <u>Devices for Setting Angles of Attack on Foils</u> (see Fig. VII)

A description of the equipment used in this thesis

FIGURE VII

Equipment and Set-up for Setting Angles of Attack



Note spirit level and declivity boards on table.

must include those devices used for setting angles of attack on the foils. Perhaps an enumeration of how a given angle of attack is set is the best way to present the description.

A small vise was first secured to a table, and then in the jaws of the vise was set a wooden block to which had been secured a small length of 1-inch sail track. By means of a spirit level, this block was levelled, with the track in an inverted position. Thereafter, the foil support device was attached to the track.

Next, a foil was screwed into position between the arms of the support device. Then, in order to set a given angle of attack, a previously prepared declivity board was set upon the lower face of the foil which was actually in an uppermost position. The spirit level was next set upon this declivity board, and the foil was rotated until the spirit level became level, indicating that the desired angle was set. The one disadvantage of this method was that it necessitated removal of the foil and foil support device from the model if it was desired to check the setting between runs. It was found that accurate and constant fixation of the foil was definitely achieved; however, the author must concede that even more accurate and more simple means of setting angles

of attack and maintaining them can be devised if so desired.

II. PROCEDURE

The INTRODUCTION to this thesis has indicated that for a family of five hydrofoils, all of the same basic shape, an investigation was made to determine what effects on total resistance were realized when these foils were mounted aft on a fine-lined transom-stern model. Additionally, it was stated that only model speeds corresponding to 15 knots and 32 knots were to be considered. Further, for each foil an evaluation was to be made of the effects on total resistance resulting from varying the angle of attack, longitudinal position, and depth of submergence.

With the above requirements in mind a procedure was therefore set up which allowed consideration of one variable at a time, while the remaining two variables were held constant. In this manner, the optimum value of one variable, corresponding to certain constant values of the remaining two, was found. Thereafter, this optimum value of the first variable was used as one of the two constants, and then a second variable was considered until an optimum value was found for it. Of course, this procedure was continued for the third variable.

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Now it is readily apparent that this is an iterative solution, and it could have been repeated any number of times desired. In order to carry the first solution through as has been done in this thesis, it was necessary to conduct no less than 337 runs, so it is clear that the number of variables must be limited, or the testing program will become excessively involved.

The model speeds corresponding to 15 and 32 knots on the full size ship were 1.370 and 2.920 knots. Now for any given position of a foil on the model the desired data was the value of the total resistance coefficient at either 1.370 or 2.920 knots. This was most easily found by towing the model at speeds which bracketed those mentioned, and then plotting curves of C_T versus speed-length ratio. The C_T value of the curve at the speed range being considered was then read directly.

Once the value of the total resistance coefficient for a given foil position at either of the speed ranges was found, it next followed that a curve of C_T versus the variable being considered should be plotted. From the shape of this curve it was possible to determine the optimum value of the variable for minimum C_T. This approach was employed in determining both the optimum longitudinal position and the optimum angle of attack for the 1 inch, 1.5 inch and 2 inch hydrofoils.

Only in the case of the 1-inch foil was the depth of submergence allowed to vary. References (3) and (9) had indicated that the hydrofoils should not be closer to the free surface of the water than one chord length. Now in order to maintain a realistic approach to possible application of hydrofoils to full size vessels it was made a rigid stipulation that the foils should not be set below the base line of the model. This base line was 1.761 inches below the free surface, and therefore only the 1.5 inch and 1 inch foils were of small enough chord length to permit any movement between limits of one chord length and the base line. Since the allowable downward movement of the 1.5 inch foil was only 0.261 inches, it was decided to keep the depth of submergence constant at 1.761 inches for all foils except the 1 inch foil. In the case of the 1 inch foil the depth of submergence was allowed to vary between the limits of 1 inch and 1.761 inches.

After completion of the optimum attack angle and optimum longitudinal position tests in the 32 knot range on the 1 inch, 1.5 inch and 2 inch stern hydrofoils, it became clear that no reduction in total resistance coefficient was being achieved by the use of the stern hydrofoils. Furthermore, the data that had been collected indicated that the 2.5 inch and 3.0 inch foils would most

probably produce even worse results. Hence no attempt was made to carry out optimum attack angle and longitudinal position tests on these remaining foils. Instead, on the basis of the curves already plotted, their optimum positions were estimated by extrapolation. They were then set at these positions and tested in the 32 knot range. In the case of the 3 inch foil it was also tested in the 15 knot range. Full details of the series of 14 tests devoted to stern hydrofoil investigation will be found in Appendix D.

The lack of success achieved with stern hydrofoils on this particular fine-lined model served to arouse curiosity as to whether or not bow hydrofoils might not be more successful. As a final phase of this work, it was therefore decided to determine what results could be achieved by mounting the 2 inch foil on the bow of the model. Slight modifications to the hydrofoil support device in the form of lengthened support arms were necessary. Also, due to the sheer curve of the bow, the support track was mounted somewhat differently. These details will be noted in Figure VIII.

The 2 inch bow hydrofoil was maintained at a constant depth of submergence of 1.761 inches. In the exact same manner as was done in the stern investigation, optimum longitudinal position tests were first carried out followed by optimum attack angle tests.

FIGURE VIII

Details of Bow Hydrofoil Support Device

Showing the 2.0 inch foil set at keel depth

[illegible]

[illegible]

[illegible]

III. RESULTS

The results of the various tests conducted on the family of hydrofoils and model DTMB-DD332 are presented in the form of curves. The following listing will serve to describe the purpose of each curve and will indicate the sources of data if it is a curve derived from another curve or curves. These results all pertain to the model only, and in order are:

A. Stern Hydrofoils

1. Figure IX. C_T versus $V/\sqrt{L}$ for the model without and with sandstrips at the beginning of the testing program on 6 March 1954. Also shown on this plot is a re-evaluation of the model's sanded resistance at the 15 and 32 knot ranges. This re-evaluation was made on 2 April 1954, and 10 April 1954, and serves to indicate the increase in total resistance that resulted from severe cracking of the bottom paint on the model.

2. Figure X. C_T versus $V/\sqrt{L}$ for the sanded model with bow and stern hydrofoil support devices attached at the 15 knot range. Also shown is the re-evaluation of the model's total resistance coefficient after subsequent cracking of the bottom paint.

3. Figure XI. Same as Figure X above, except that this is for the 32 knot range.

4. Figure XII. C_T versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 1 inch hydrofoil at various positions as indicated on the plot.

5. Figure XIII. C_T versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 1.5 inch hydrofoil at various positions as indicated on the plot.

6. Figure XIV. C_T versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 2.0 inch hydrofoil at various positions as indicated on the plot.

7. Figure XV. C_T (at 32 knot range) versus longitudinal position of hydrofoil. This is a family of three curves pertaining to the 1.0, 1.5, and 2.0 inch hydrofoils. They show the effect of varying the hydrofoil's longitudinal position and also show that longitudinal position at which the minimum value of C_T will occur for each foil at the particular attack angle set. Points on these curves are the values of C_T at the 32 knot range as found in Figures XII, XIII, and XIV.

8. Figure XVI. Hydrofoil chord length versus longitudinal position of hydrofoil for minimum C_T at 32 knot range. This curve shows the variation of the optimum longitudinal position for a hydrofoil as we change the chord length. By extrapolation on this curve, a prediction is made as to the optimum longitudinal position for the 2.5 and 3.0 inch hydrofoils at the 32 knot range.

9. Figure XVII. C_T (at 32 knot range) versus hydrofoil angle of attack, with hydrofoils located at their optimum longitudinal positions. This also is a family of three curves pertaining to the 1.0, 1.5, 2.0 inch hydrofoils. These curves show the effect of varying

3. Figure XI. Same as Figure X above, except that this is for the 32 knot range.

4. Figure XII. C_L versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 1 inch hydrofoil at various positions as indicated on the plot.

5. Figure XIII. C_L versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 1.5 inch hydrofoil at various positions as indicated on the plot.

6. Figure XIV. C_L versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 2.0 inch hydrofoil at various positions as indicated on the plot.

7. Figure XV. C_L (at 32 knot range) versus longitudinal position of hydrofoil. This is a family of three curves pertaining to the 1.0, 1.5, and 2.0 inch hydrofoils. They show the effect of varying the hydrofoil's longitudinal position and also show that longitudinal position at which the minimum value of C_L will occur for each foil at the particular attack angle set. Points on these curves are the values of C_L at the 32 knot range as found in Figures XII, XIII, and XIV.

8. Figure XVI. Hydrofoil chord length versus longitudinal position of hydrofoil for minimum C_L at 32 knot range. This curve shows the variation of the optimum longitudinal position for a hydrofoil as we change the chord length. By extrapolating on this curve, a prediction is made as to the optimum longitudinal position for the 2.5 and 3.0 inch hydrofoils at the 32 knot range.

9. Figure XVII. C_L (at 32 knot range) versus hydrofoil angle of attack, with hydrofoils located at their optimum longitudinal positions. This also is a family of three curves pertaining to the 1.0, 1.5, 2.0 inch hydrofoils. These curves show the effect of varying

the hydrofoil's angle of attack, and also show the angle of attack at which the absolute minimum value of C_T will occur for each foil. As in Figure XV, the points on these curves are the values of C_T at the 32 knot range as found in Figures XII, XIII, and XIV. It is to be noted that each foil was located at its optimum longitudinal position, hence the values of C_T at the optimum angles of attack represent the lowest possible values of C_T that can be achieved at the 32 knot range for the particular foils being considered.

10. Figure XVIII. Hydrofoil chord length versus angle of attack of hydrofoil for minimum C_T at the 32 knot range. This curve shows the variation of the optimum angle of attack for a hydrofoil at the 32 knot range as we change the chord. By extrapolation on this curve, a prediction is made as to the optimum angle of attack for the 2.5 and 3.0 inch hydrofoils at the 32 knot range.

11. Figure XIX. C_T versus $V/\sqrt{L}$ at 32 knot range for the 2.5 and 3.0 inch hydrofoils located at their optimum positions. These optimum positions were determined by extrapolation in Figures XVI and XVIII. Also (in dashed lines) will be found extrapolated curves of C_T versus V/ L for the 1.0, 1.5, and 2.0 inch foils. These curves have one known point, the 32 knot range lowest possible value of C_T. Their slope and shape is based on that indicated in Figures XII, XIII and XIV. They are shown merely for comparison purposes.

12. Figure XX. Chord length versus absolute minimum C_T at the 32 knot range. The points on this curve correspond to the 32 knot range lowest possible values of C_T as indicated in Figure XIX. Corresponding to each chord length, a short dashed line has been drawn in at the value of C_T which was to be expected due to the increased frictional resistance arising from the

the hydrofoil's angle of attack, they also show the angle of attack at which the absolute minimum value of C_T will occur for each foil. As in Figure XV, the points on these curves are the values of C_T at the 32 knot range as found in Figures XII, XIII, and XIV. It is to be noted that each foil was located at its optimum longitudinal position; hence the values of C_T at the optimum angles of attack represent the lowest possible values of C_T that can be achieved at the 32 knot range for the particular foils being considered.

10. Figure XVIII. Represents chord length versus angle of attack of hydrofoil for minimum C_T at the 32 knot range. This curve shows the variation of the optimum angle of attack for a hydrofoil at the 32 knot range as we change the chord. By extrapolation on this curve, a prediction is made as to the optimum angle of attack for the 0.5 and 1.0 inch hydrofoils at the 32 knot range.

11. Figure XIX. C_T versus $V/\sqrt{L}$ at 32 knot range for the 1.5 and 3.0 inch hydrofoils located at their optimum positions. These optimum positions were determined by extrapolation in Figures XVI and XVIII. Also (in dashed lines) will be found extrapolated curves of C_T versus $V/\sqrt{L}$ for the 0.5, 1.0, and 2.0 inch foils. These curves have one known point, the 32 knot range lowest possible value of C_T. Their slope and shape is based on that indicated in Figures XII, XIII and XIV. They are shown merely for comparison purposes.

12. Figure XX. Chord length versus absolute minimum C_T at the 32 knot range. The points on this curve correspond to the 32 knot range lowest possible values of C_T as indicated in Figure XIX. Corresponding to each chord length, a fairly smooth line has been drawn in of the value of C_T which may be expected due to any inspection of curves and extrapolated values from the

added wetted surface of the hydrofoil. (See Appendix E). This is the most important curve in this thesis and will be considered in some detail in the DISCUSSION OF RESULTS.

13. Figure XXI. C_T versus $V/\sqrt{L}$ at the 15 knot range for 1.0 and 3.0 inch hydrofoils located at their optimum positions as found in the 32 knot range tests. This curve is intended to show the range of C_T values to be expected in the high frictional resistance region.

14. Figure XXII. C_T versus $V/\sqrt{L}$ at the 32 knot range for the 1.0 inch hydrofoil at its optimum position. This plot shows the effect on resistance that results from varying the depth of submergence of the 1 inch hydrofoil.

B. Bow Hydrofoils

1. Figure XXIII. C_T versus $V/\sqrt{L}$ at 32 knot range, showing intercept curves for the 2 inch bow hydrofoil, at various positions as indicated on the plot.

2. Figure XXIV. C_T (at 32 knot range) versus longitudinal position of the 2 inch bow hydrofoil. From this curve is obtained the optimum longitudinal position for minimum C_T. Shown on the plot is the predicted optimum longitudinal position. See Appendix F for details of the basis for this prediction.

3. Figure XXV. C_T (at 32 knot range) versus angle of attack for the 2 inch bow hydrofoil located at its optimum longitudinal position. This curve shows the absolute minimum value of C_T that can be achieved with the

2 inch bow hydrofoil. A dashed line is also drawn in to show the increase in C_T that was to be expected due to added frictional resistance arising from an increase in wetted surface.

The foregoing represent the graphical presentation of the findings reached in this thesis. In summary, the most significant figures are:

Figure XX,	Lowest C_T to be expected for each stern hydrofoil chord length at 32 knot range.
Figure XXI,	Magnitude of C_T produced by stern hydrofoils in 15 knot range.
Figure XXII,	Effect of variation of depth of submergence of a stern hydrofoil.
Figure XXIV,	Accuracy achieved in predicting optimum location for bow hydrofoil.
Figure XXV,	Lowest C_T to be expected with a 2 inch bow hydrofoil.

FIGURE IX.

C_T VS. $V/\sqrt{L}$ FOR THE MODEL WITH & WITHOUT SAND STRIPS

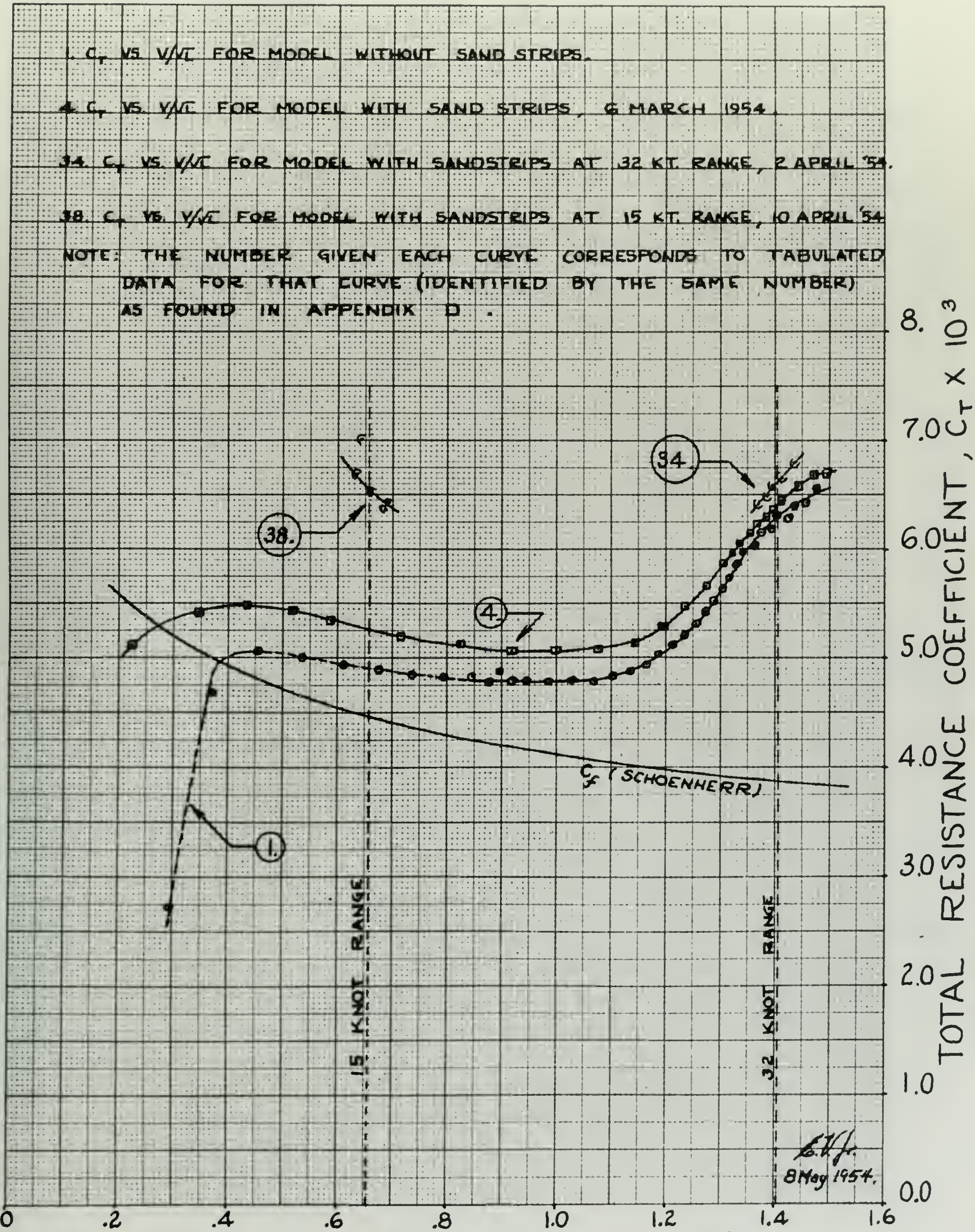


FIGURE X.

C_T VS. $V/\sqrt{L}$ FOR THE SANDED MODEL WITH & WITHOUT STERN HYDROFOIL SUPPORT DEVICE AT THE 15 KT. RANGE

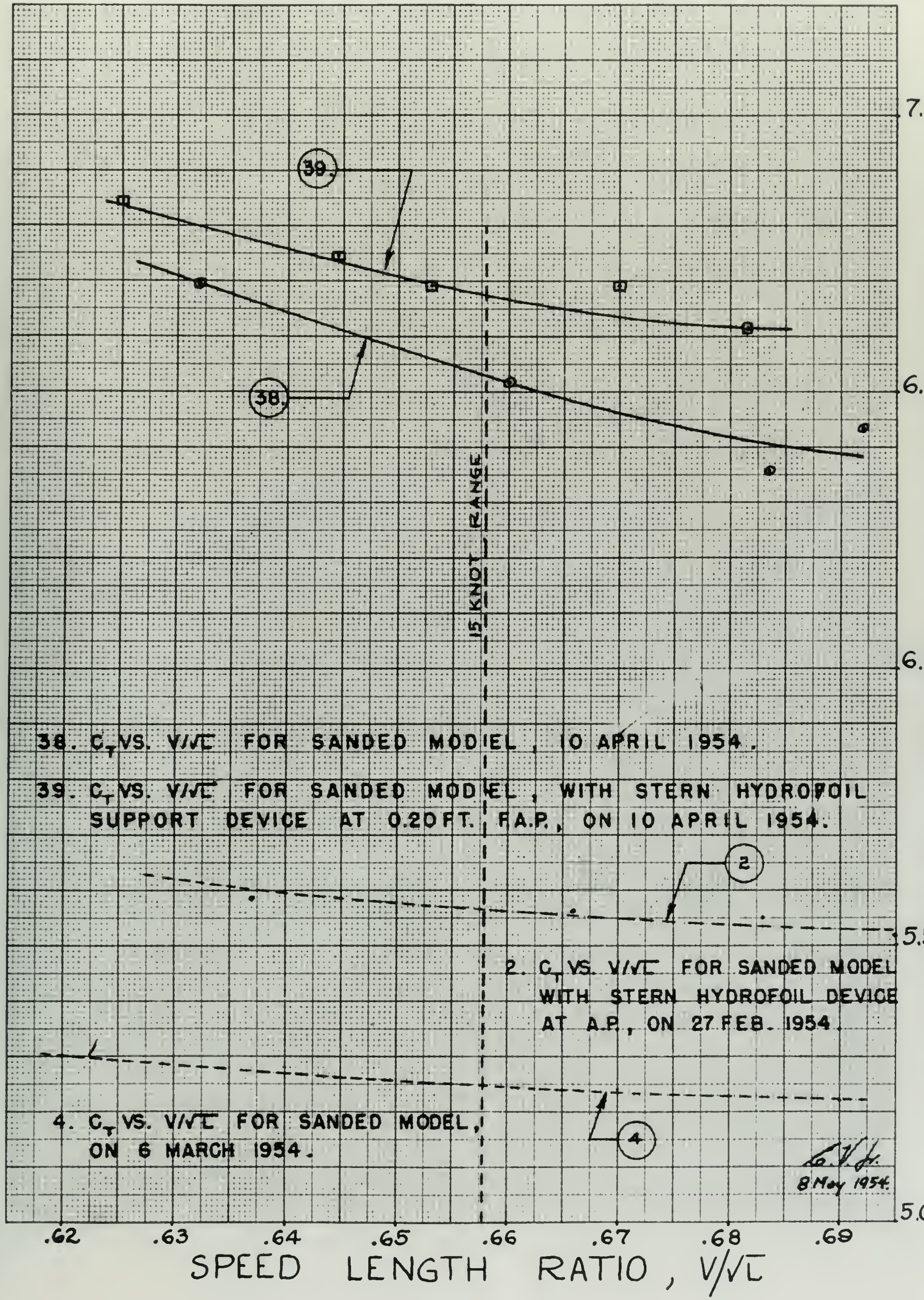


FIGURE XI.

ADDED RESISTANCE CAUSED BY THE HYDROFOIL SUPPORT DEVICES

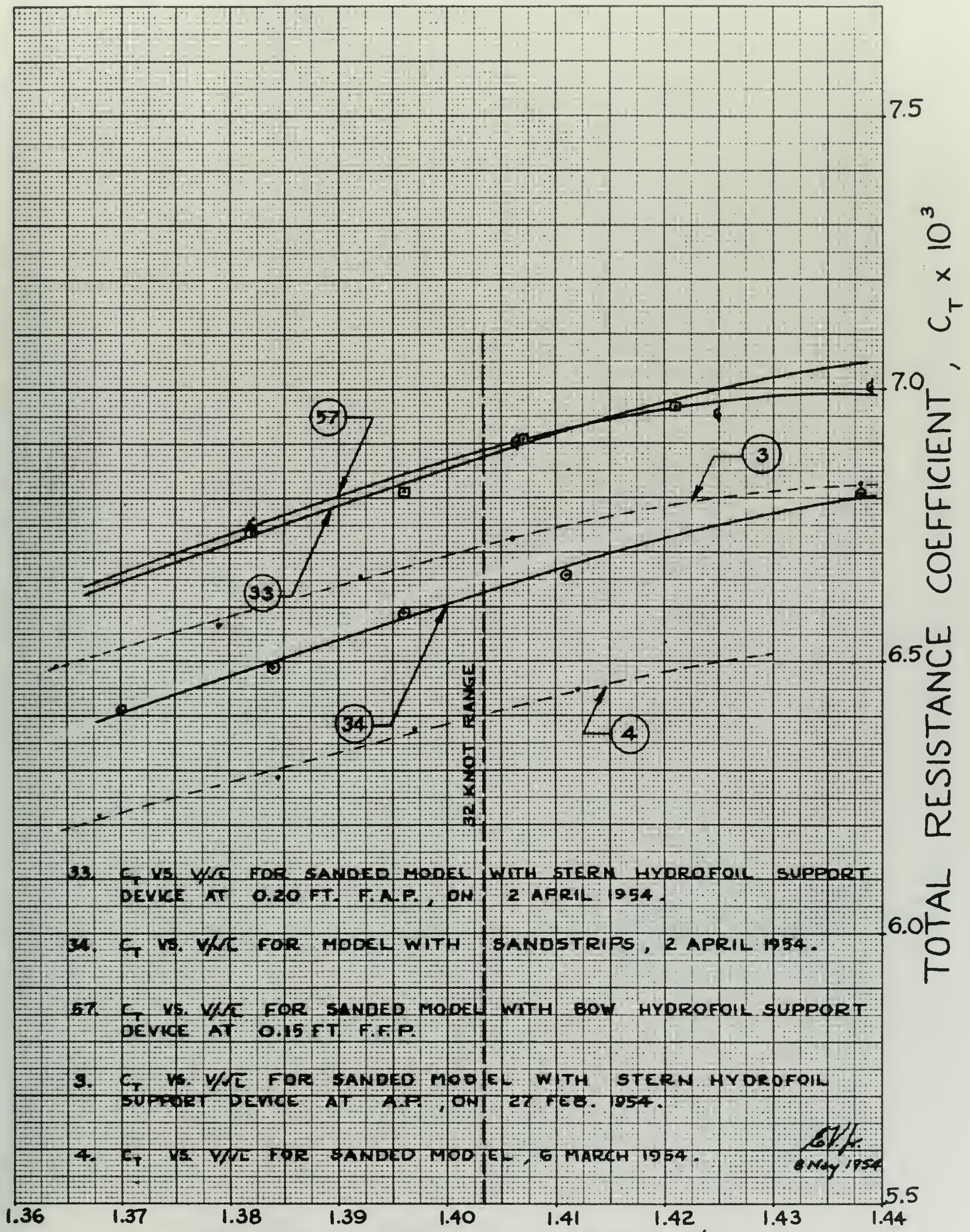


FIGURE XII.

32 KT. RANGE INTERCEPT CURVES FOR 1.0 INCH HYDROFOIL

CURVE	ℓ	α	h	$C_T \times 10^3$ @ 32k
20	.015' FAP	−2.18°	1 INCH	7.534
21	.25' FAP	−2.18°	"	7.479
22	.35' FAP	−2.18°	"	7.500
23	.425' FAP	−2.18°	"	7.706
24	.05' FAP	−2.18°	"	7.648
25	.05' AAP	−2.18°	"	7.507
26	.15' AAP	−2.18°	"	7.616
27	.30' AAP	−2.18°	"	7.742
28	.20' FAP	−4.18°	"	7.389
29	.20' FAP	−6.36°	"	7.615
30	.20' FAP	0°	"	7.506
31	.20' FAP	+2°	"	7.761
32	.20' FAP	+4°	"	8.030
33	SANDED MODEL + STERN HYDROFOIL SUPPORT DEVICE.			6.880

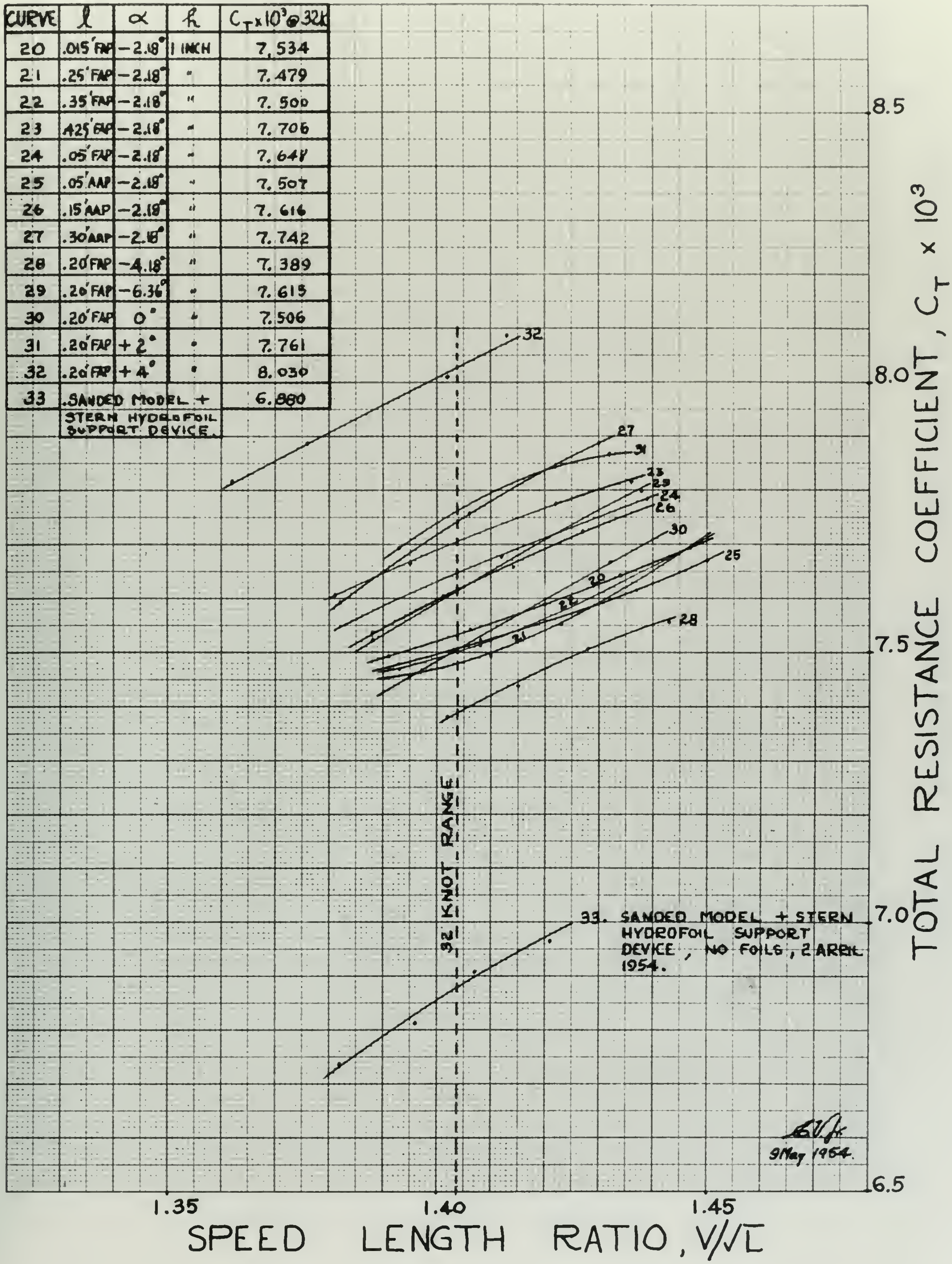
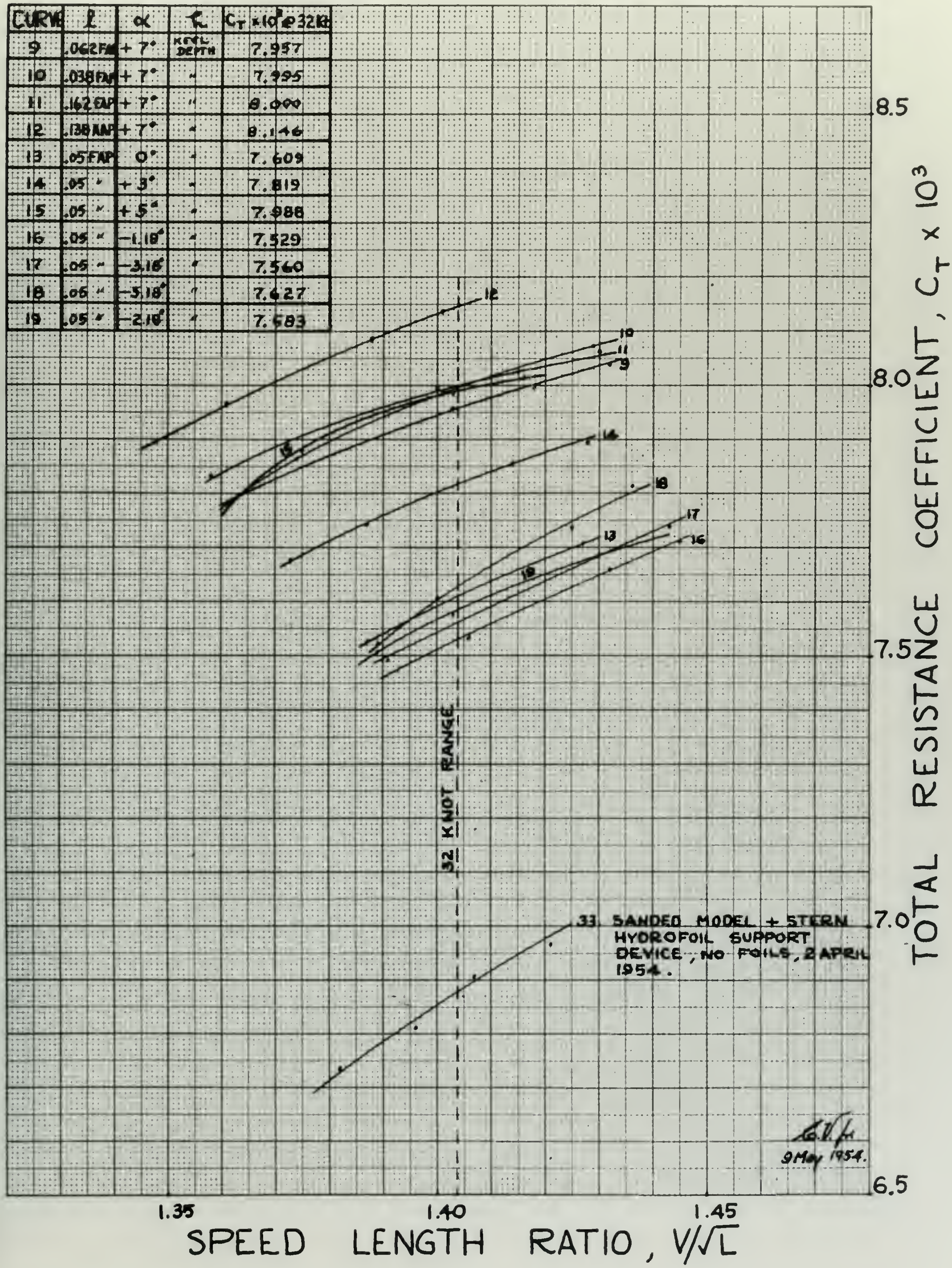


FIGURE XIII.

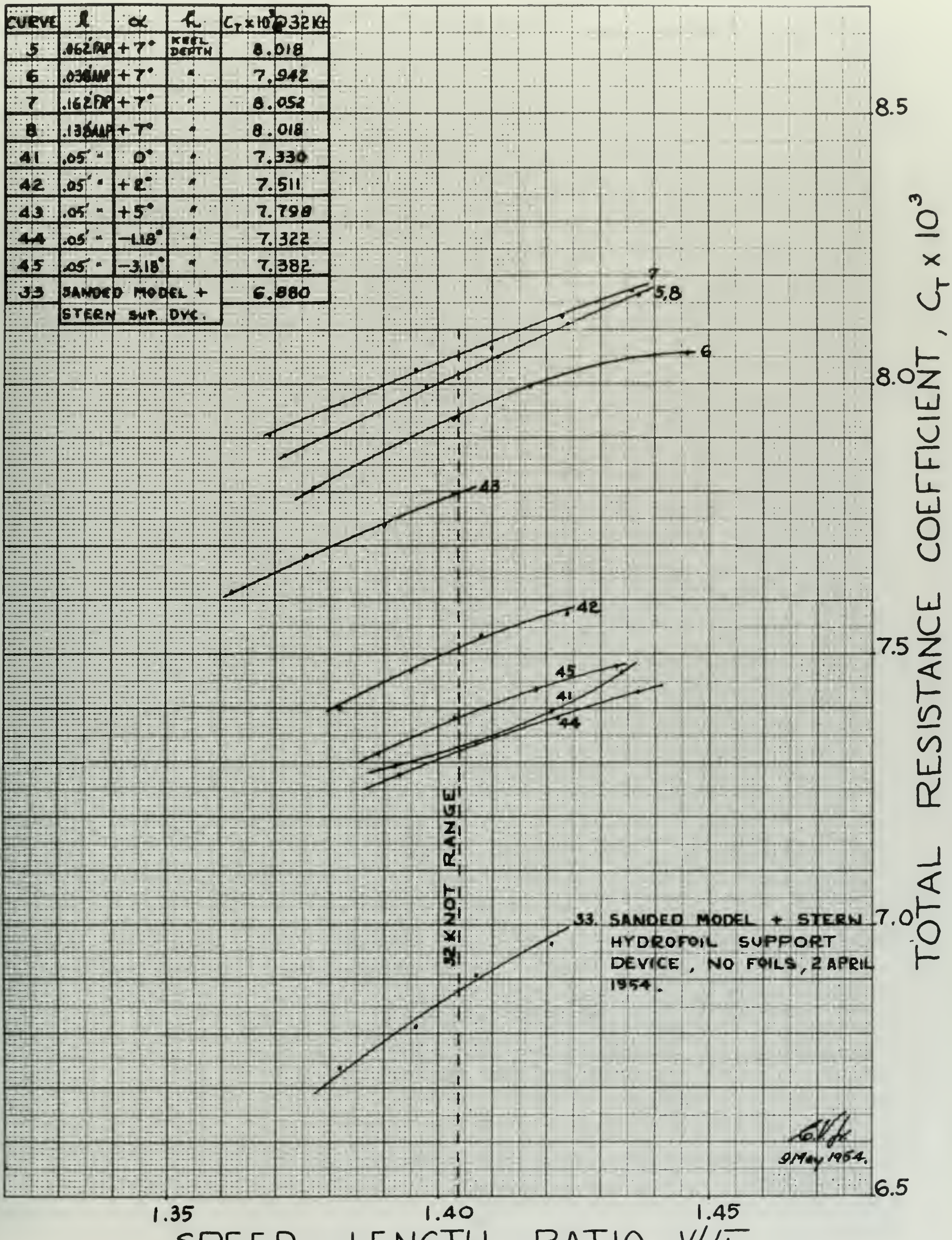
32 KT. RANGE INTERCEPT CURVES FOR 1.5 IN. HYDROFOIL



CURVE	ℓ	α	ξ	$C_T \times 10^3$ @ 32 K
9	.062 FAP	+ 7°	KEEL DEPTH	7.957
10	.038 FAP	+ 7°	"	7.995
11	.162 FAP	+ 7°	"	8.000
12	.138 AAP	+ 7°	"	8.146
13	.05 FAP	0°	"	7.609
14	.05 "	+ 3°	"	7.819
15	.05 "	+ 5°	"	7.988
16	.05 "	−1.18°	"	7.529
17	.05 "	−3.18°	"	7.560
18	.06 "	−5.18°	"	7.627
19	.05 "	−2.18°	"	7.583

FIGURE XIV.

32 KT. RANGE INTERCEPT CURVES FOR 2.0 IN. HYDROFOIL



CURVE	ℓ	α	h	$C_T \times 10^3$ @ 32 Kt
5	.162' FAP	+7°	KEEL DEPTH	8.018
6	.036' AAP	+7°	"	7.942
7	.162' FAP	+7°	"	8.052
8	.136' AAP	+7°	"	8.018
41	.05' "	0°	"	7.330
42	.05' "	+2°	"	7.511
43	.05' "	+5°	"	7.798
44	.05' "	−1.18°	"	7.322
45	.05' "	−3.18°	"	7.382
33	SANDED MODEL + STERN SUP. DVC.			6.880

FIGURE XV.

VARIATION OF RESISTANCE WITH CHANGE OF POSITION AT 32KT. RANGE

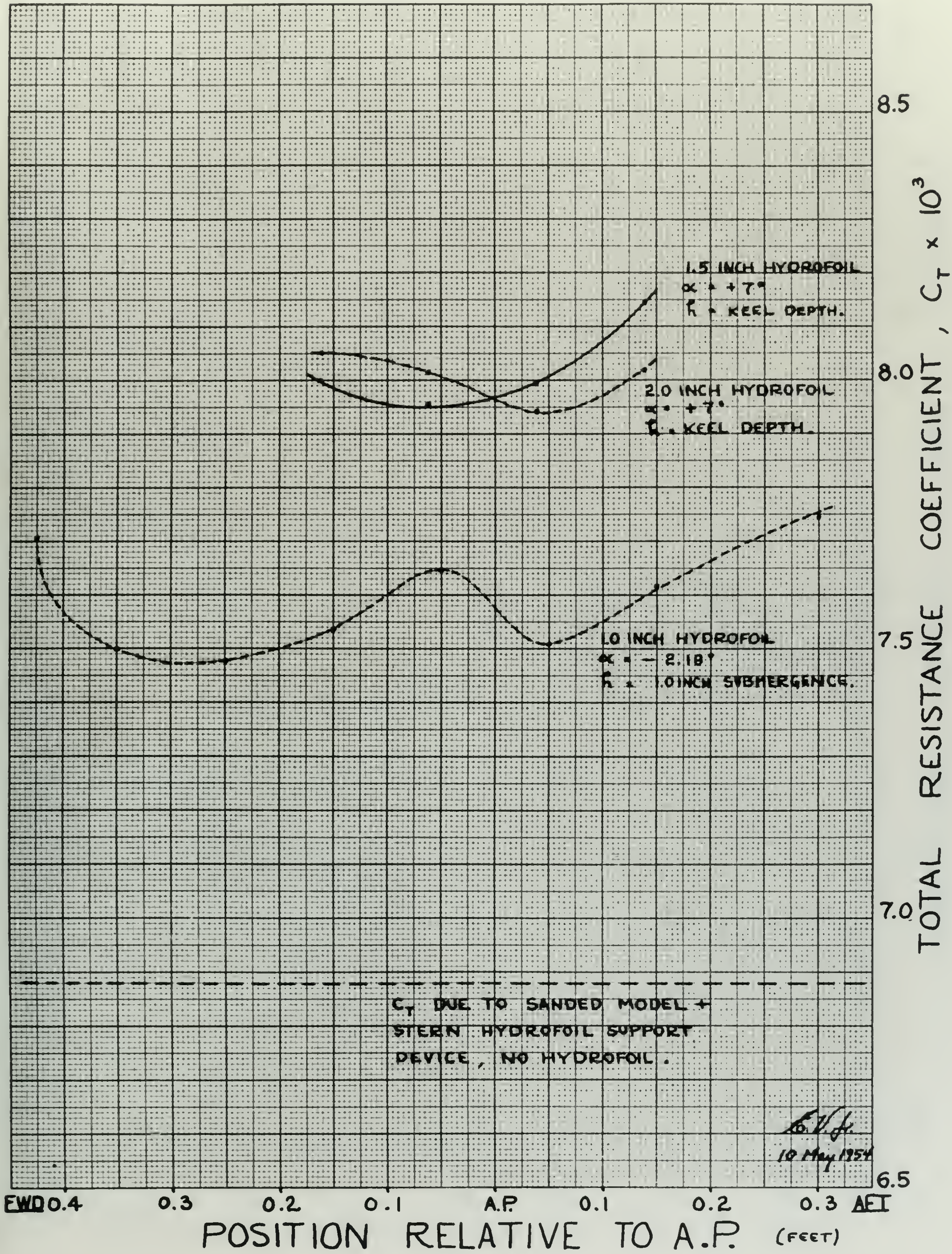


FIGURE XVI.

OPTIMUM POSITION VS. CHORD LENGTH AT 32 KT. RG.

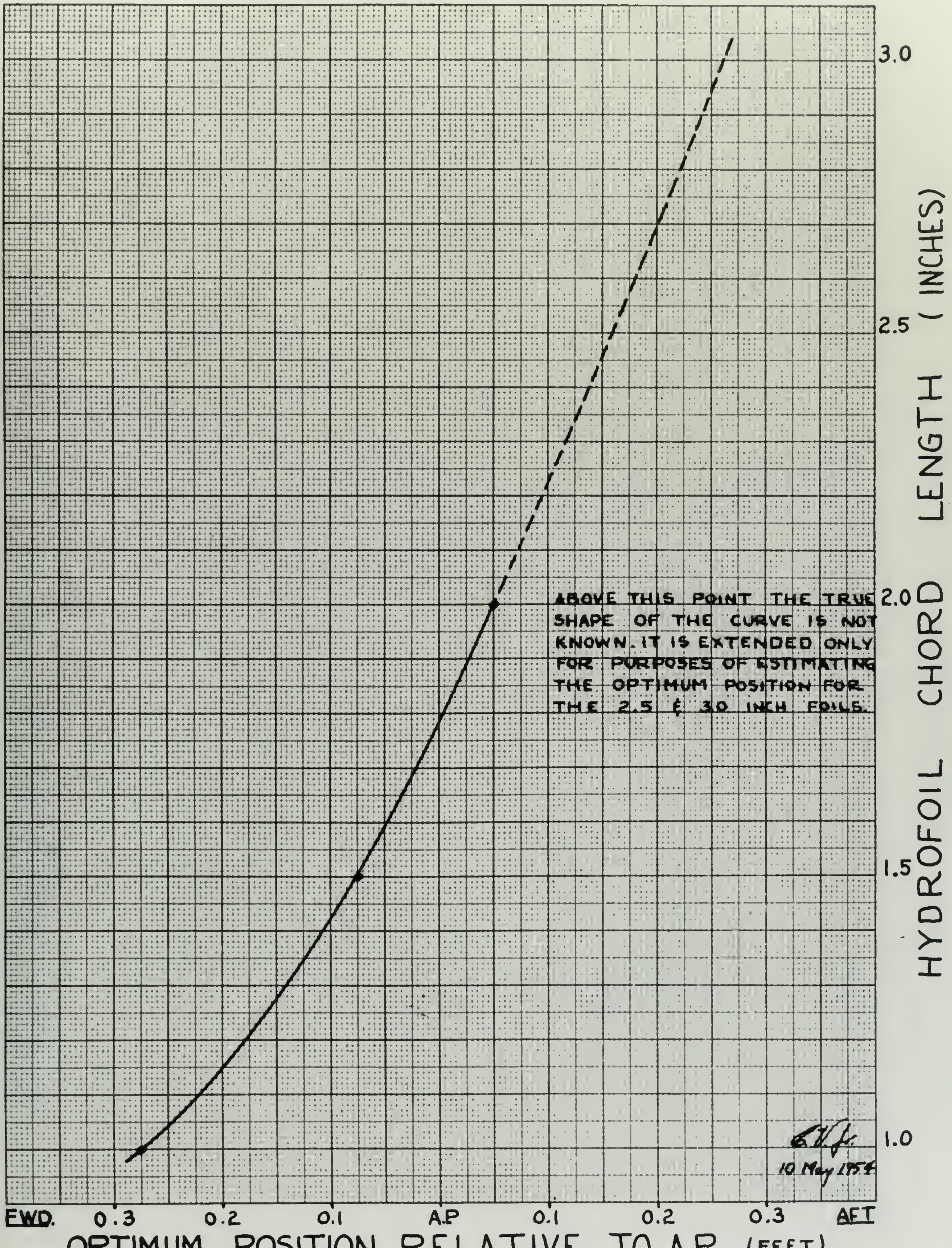


FIGURE XVII

VARIATION OF C_T WITH CHANGE OF ATTACK ANGLE AT 32KT. RG.

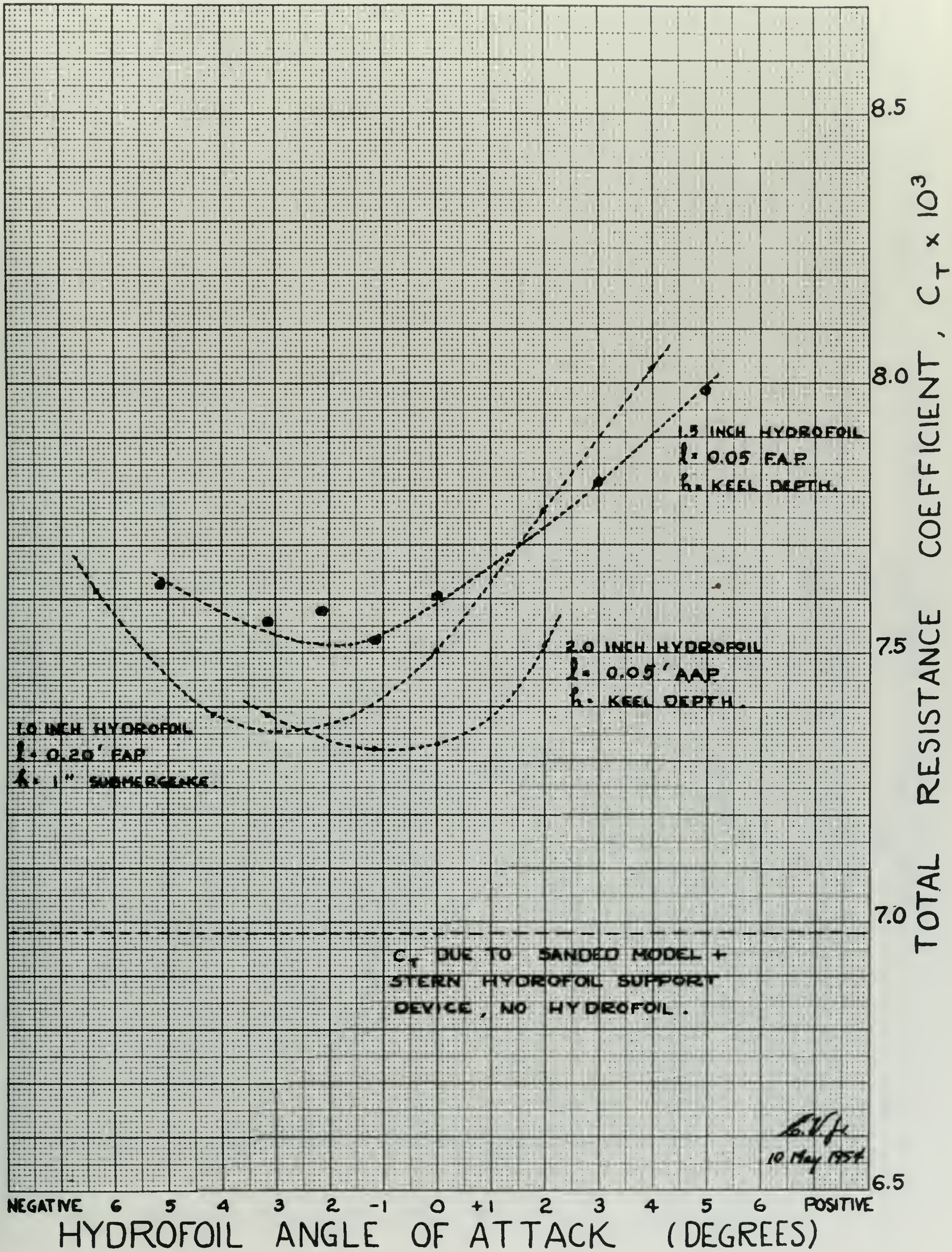


FIGURE XVIII.

OPTIMUM ANGLE OF ATTACK VS. CHORD LENGTH AT 32 KT. RG.

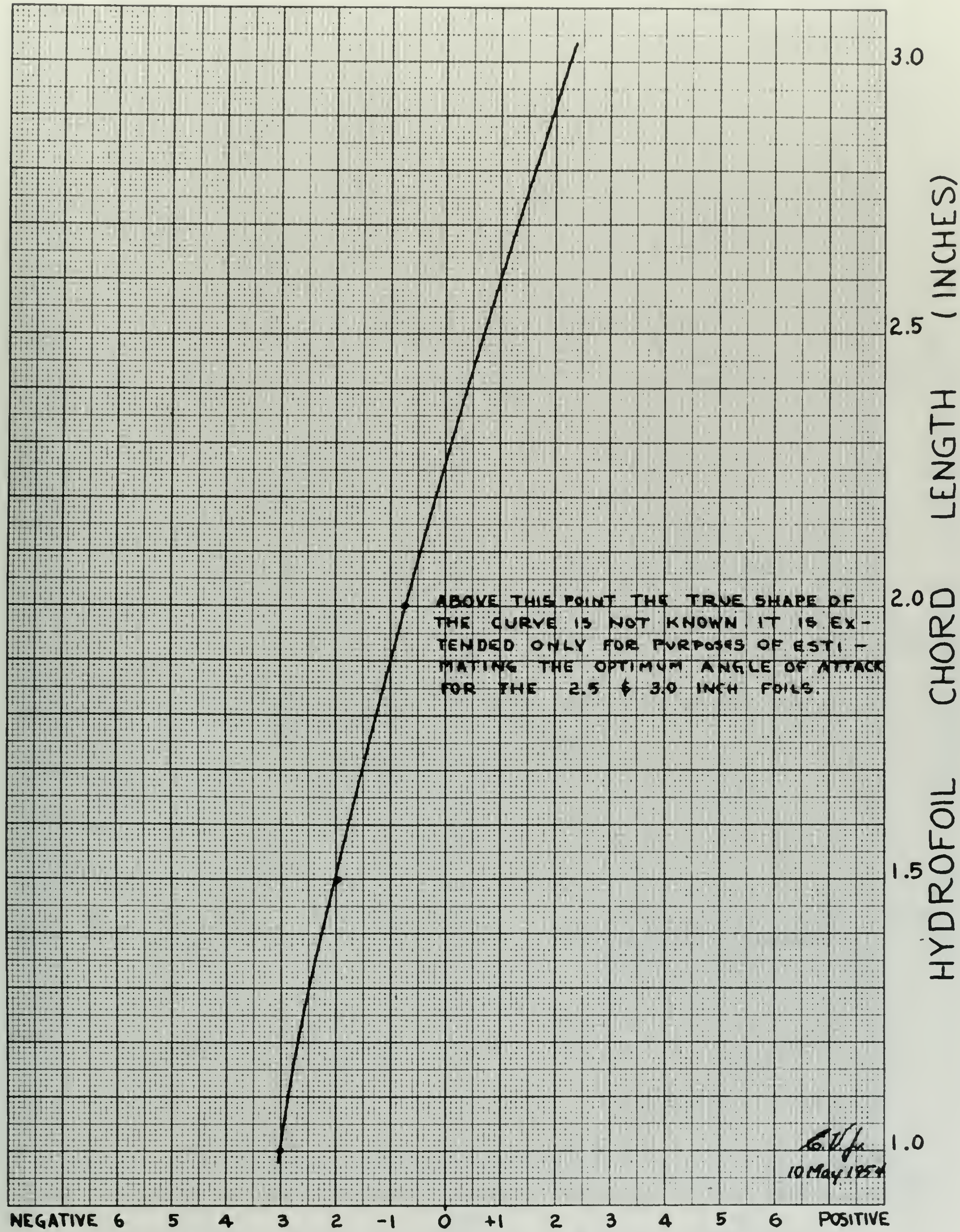


FIGURE XIX.

32 KT. RG. OPTIMUM C_T VS. $V/\sqrt{L}$ CHARACTERISTICS FOR HYDROFOILS

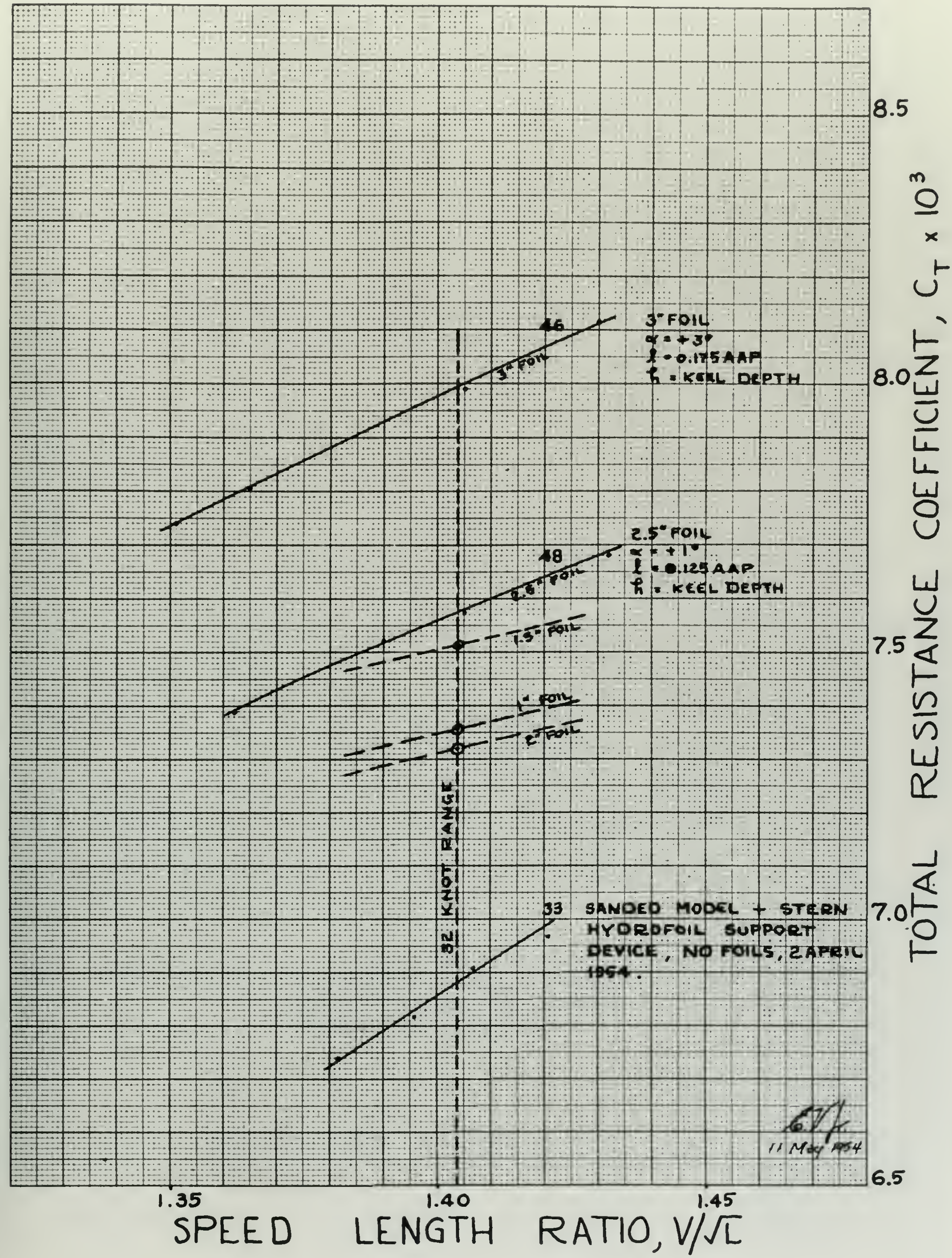


FIGURE XX.

CHORD LENGTH VS. MINIMUM C_T AT THE 32 KNOT RANGE ONLY

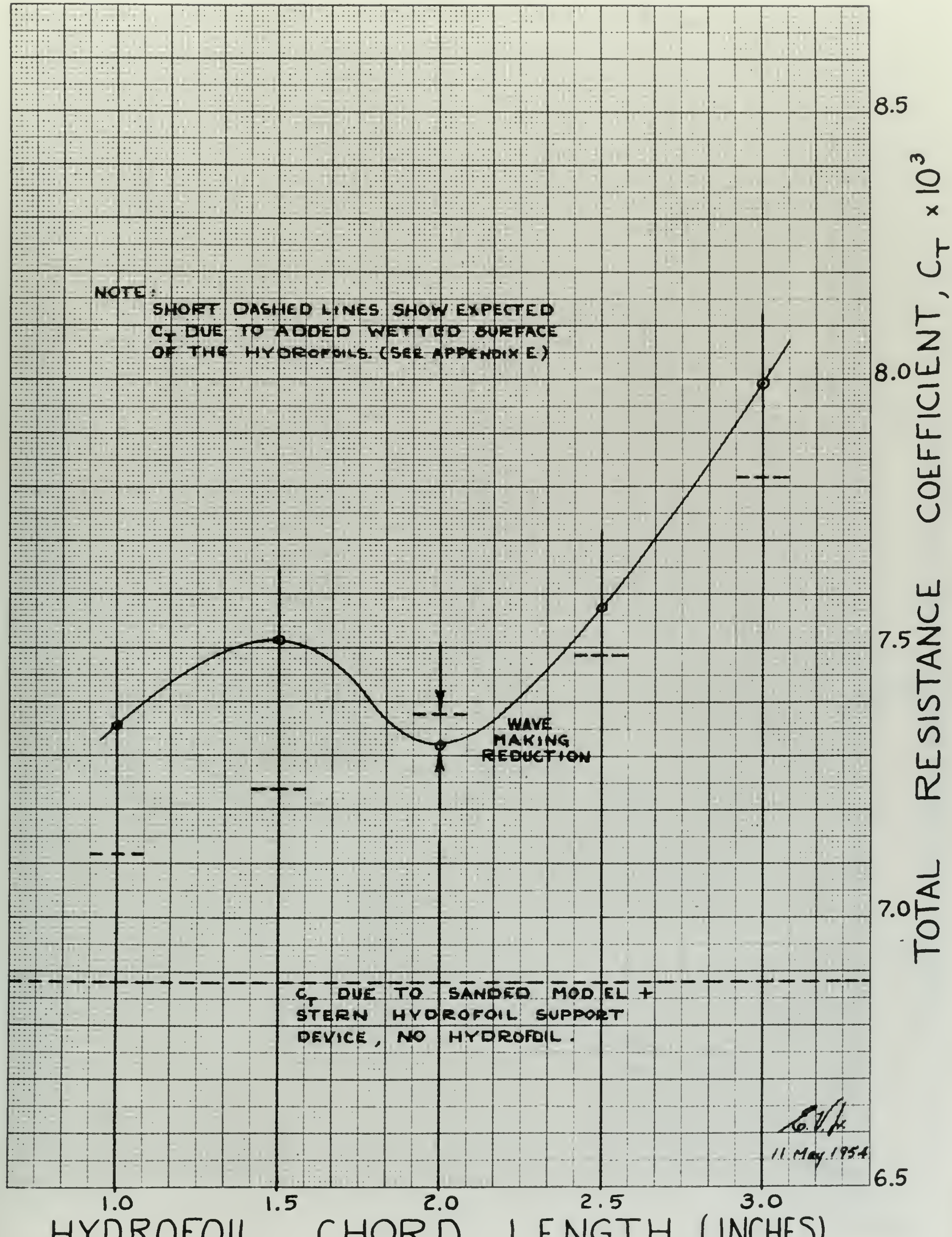


FIGURE XXI.

C_T VS. $V/\sqrt{L}$ AT 15 KT. RANGE FOR 1.0 AND 3.0 INCH HYDROFOILS

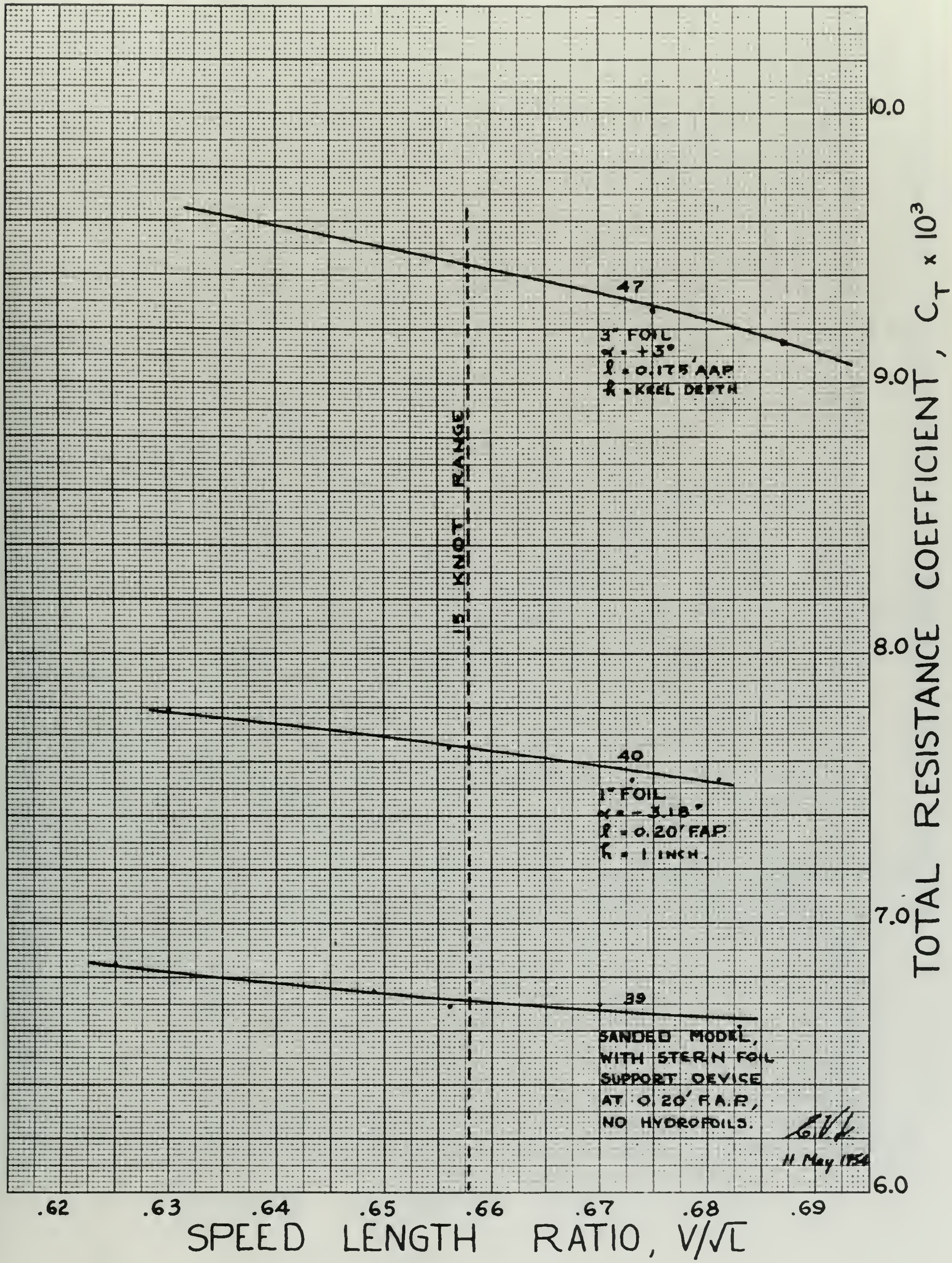


FIGURE XXII.

EFFECT ON RESISTANCE OF VARYING SUBMERGENCE DEPTH OF THE 1.0 IN. HYDROFOIL AT THE 32 KT. RANGE

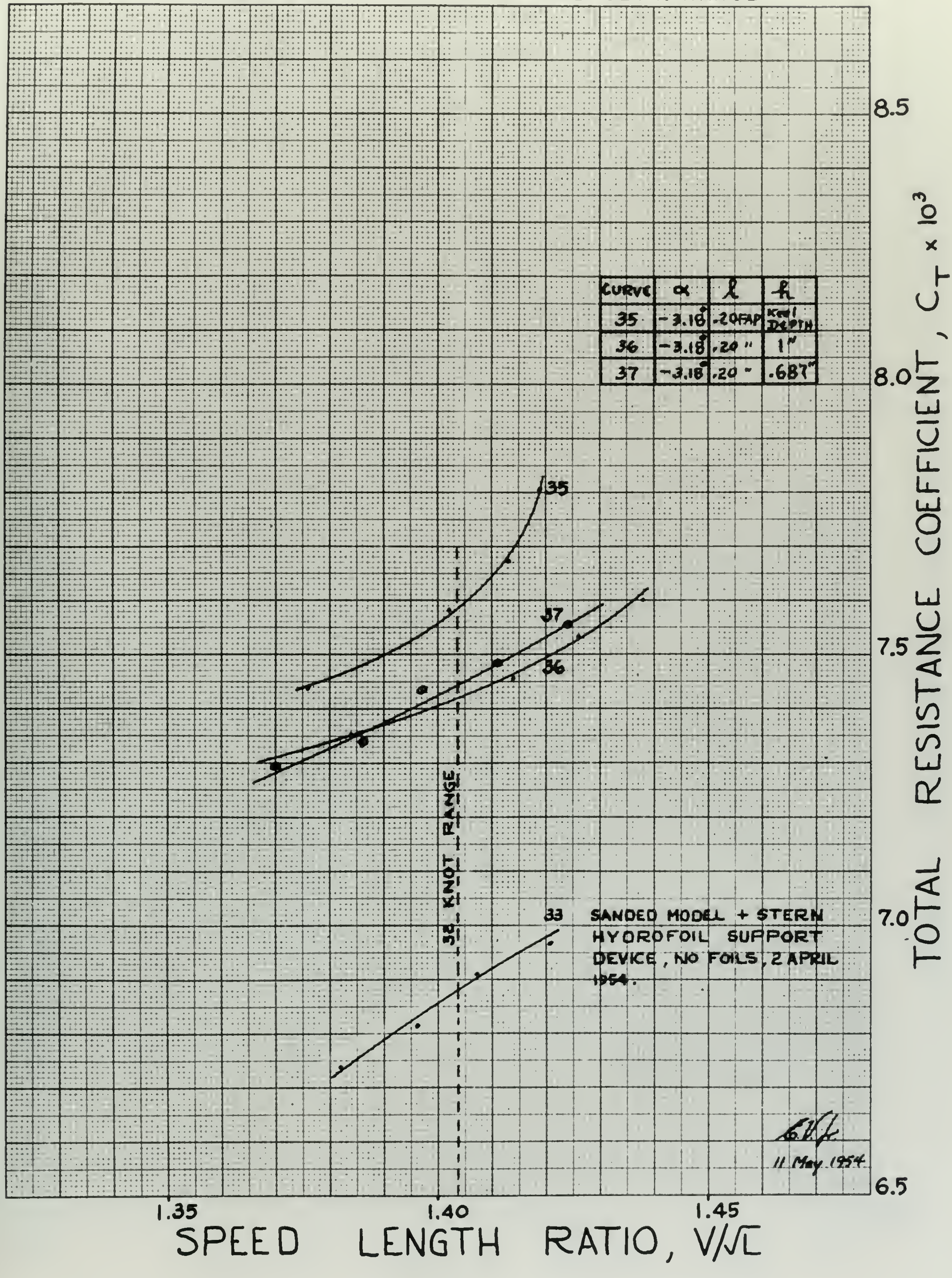


FIGURE XXIII.

32 KT. RANGE INTERCEPT CURVES FOR 2.0" BOW HYDROFOIL

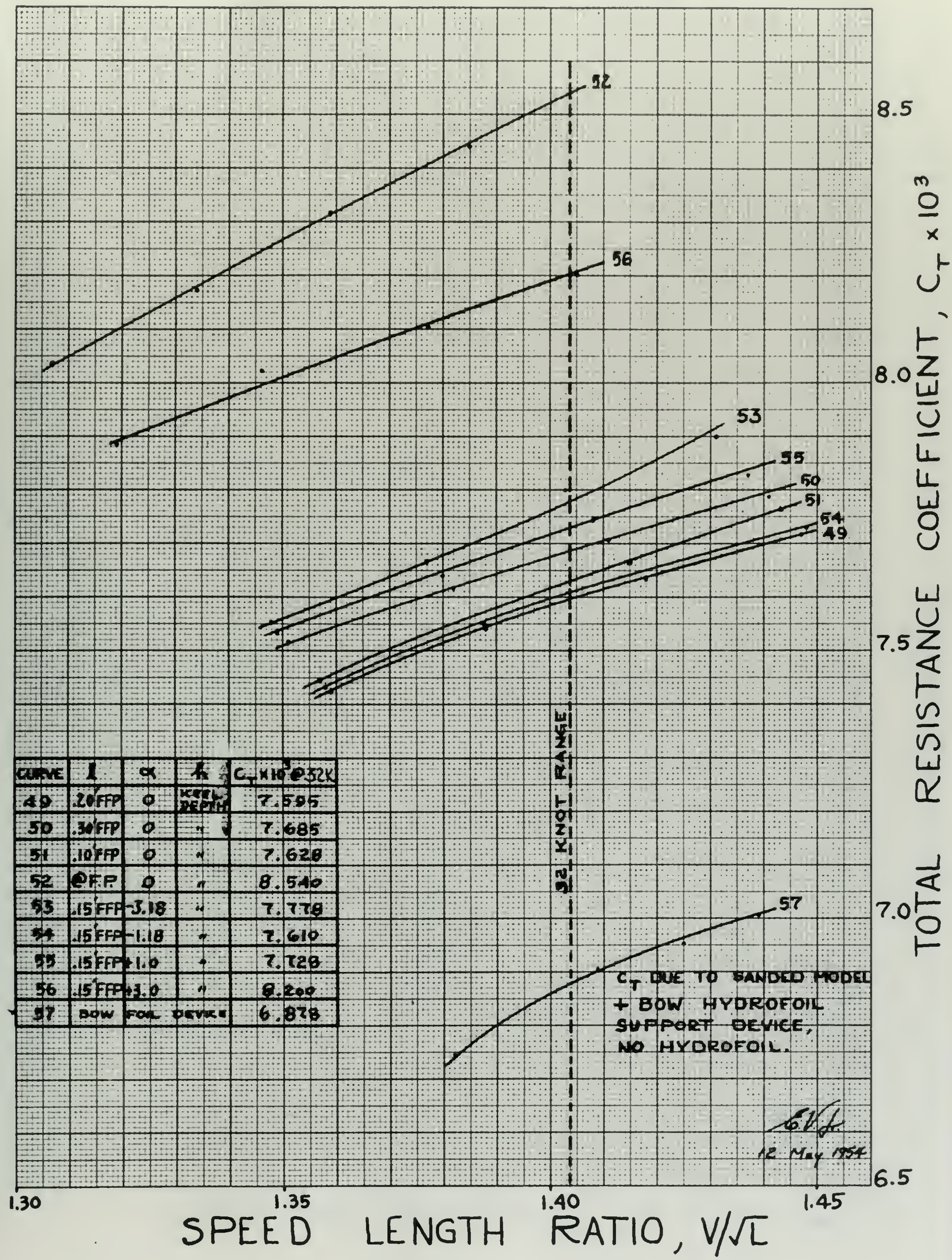


FIGURE XXIV.

VARIATION OF C_T WITH CHANGE OF POSITION OF THE 2.0" BOW HYDROFOIL AT THE 32KT. RANGE

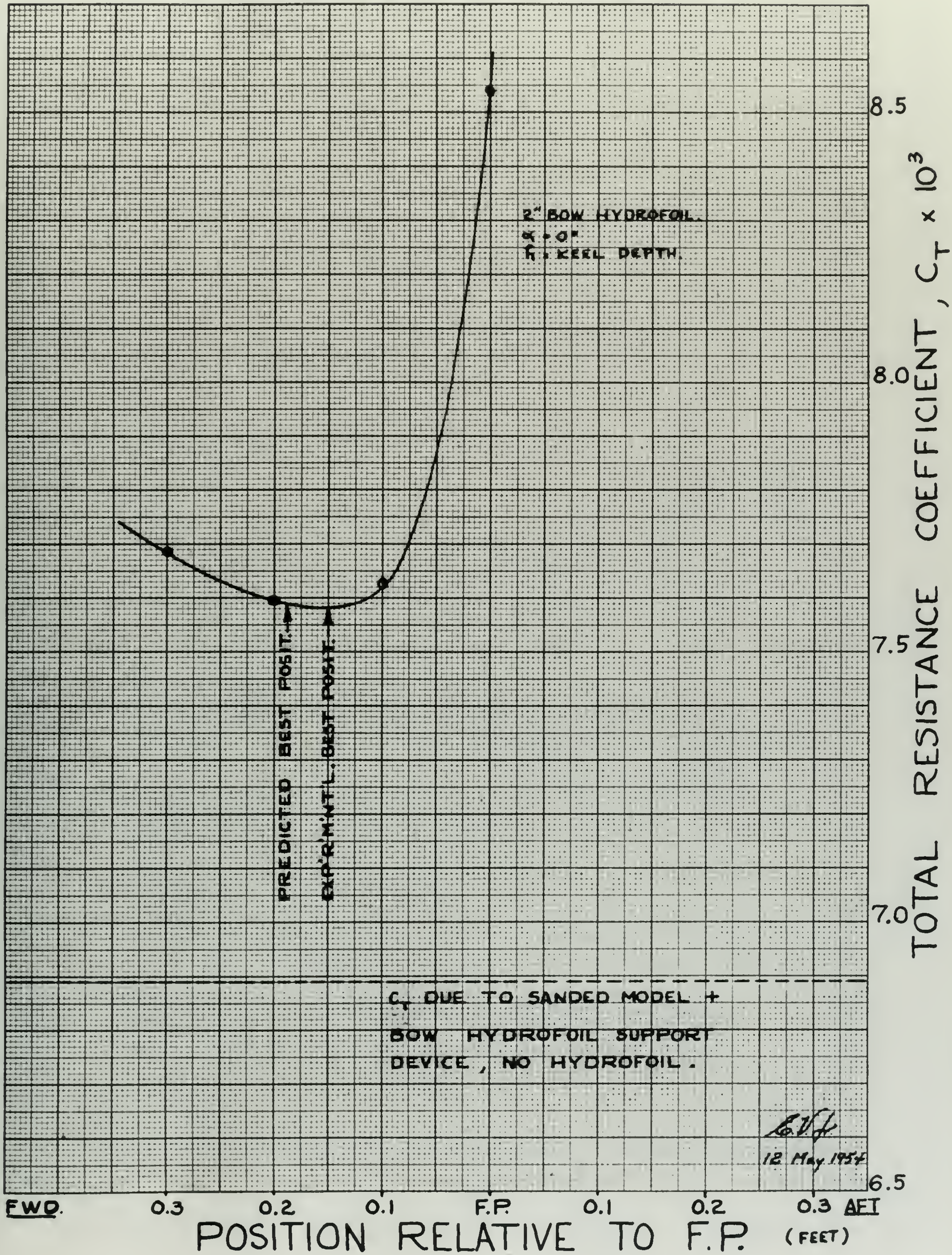
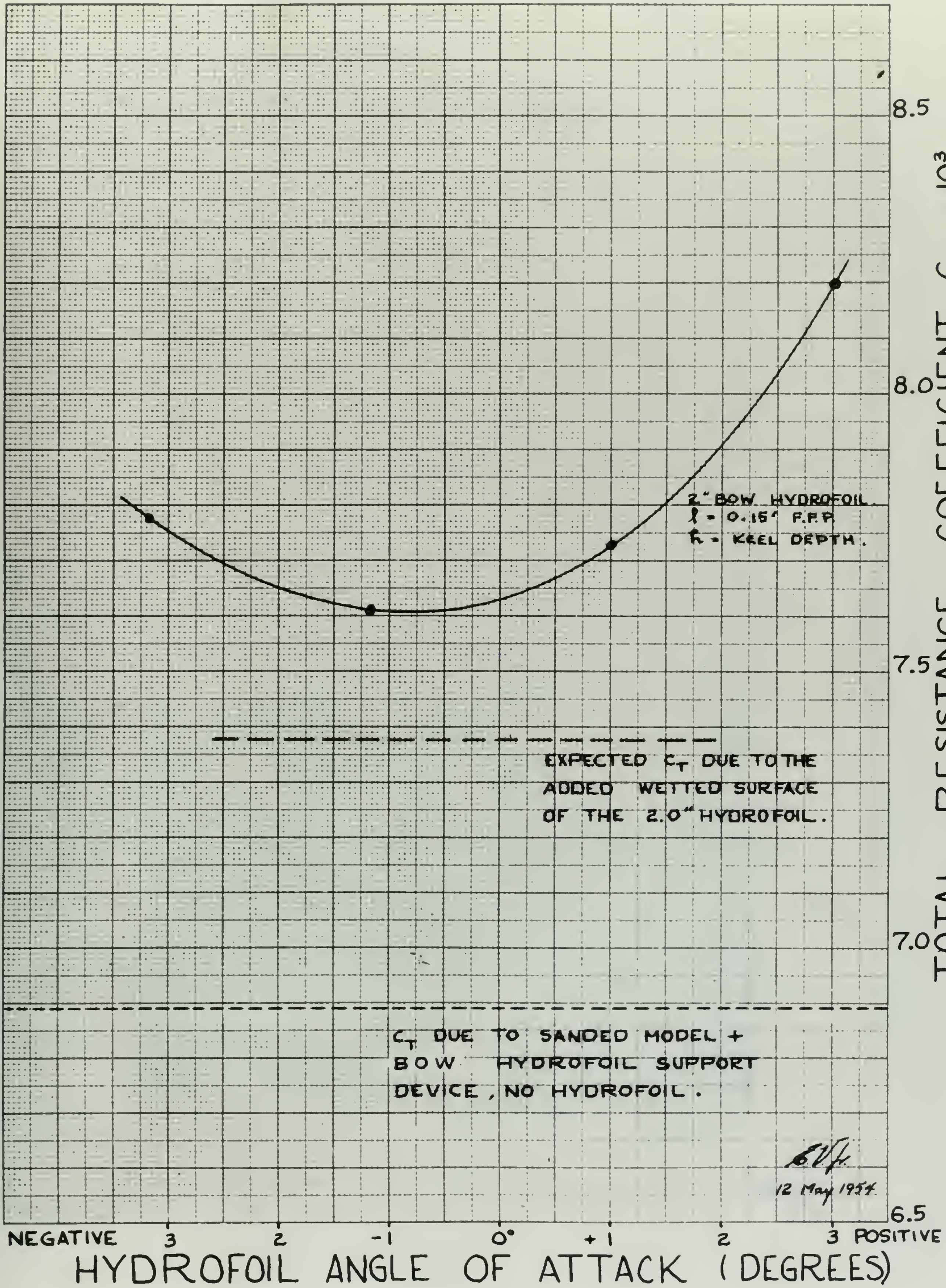


FIGURE XXV.

VARIATION OF C_T WITH CHANGE OF ATTACK ANGLE OF THE 2.0" BOW HYDROFOIL AT THE 32 KT. RANGE



IV. DISCUSSION OF RESULTS

A. Stern Hydrofoil Results

The presentation of the RESULTS section followed the chronological development of the thesis during the experimental testing stage. Accordingly, it is believed that a more pointed and well rounded analysis will result if this same chronological order is followed in this discussion.

The full range tests of C_T versus $V/\sqrt{L}$ as shown in Figure IX indicated that this particular vessel had a very well defined hump in its resistance curve that appeared to be of most significance near the 32 knot range. This of course inferred that the bow and stern transverse waves were somewhat in coincidence near this speed range. Reference (2) stated that "..... the humps in the residual resistance curves occur when the surface levels about the stern are relatively low ....." and accordingly a photograph was made to verify this statement. (See Figure XXVI).

As will be noted in this photograph the surface level aft of the model is considerably disturbed by eddies, but the level is relatively low, and at worst

FIGURE XXVI

Stern Wave Profile

Note wave hollow just aft of transom. Speed of model is 3.240 knots. (Corresponds to 35.5 knots for full size vessel).

[illegible]

[illegible]

there is only a very slight initial stern hollow. These facts tended to indicate that for this particular hull form the contribution to wave making by the after body was not nearly as significant as the contribution by the fore body. However, it remained for further testing to prove whether or not the effects of this after body contribution could be reduced by the presence of a properly positioned stern hydrofoil.

Before leaving Figure IX attention must also be focused on the changes in the sanded model's total resistance coefficient that occurred between the beginning of the testing period and the end. It will be noted that a marked increase in resistance took place, and this increase is attributed entirely to severe cracking of the paint on the bottom of the model. As the wood of the model was subjected to submersion and drying there was a resultant expansion and contraction. The bottom paint was an enamel or lacquer which was quite brittle in nature. As a consequence, it cracked, and the result was that there was a general roughening of the bottom surface.

The major portion of this cracking took place soon after the start of the testing program. Its presence was noted, but time prohibited the complete refinishing of the bottom, and the condition was accepted with full realization of its undesirability. It must be frankly

stated that this condition undoubtedly was not a static one, and hence some doubt arises as to the real condition that existed at any point in time during the testing program. It is the author's firm opinion that any error introduced by this source is of small significance and does not tend to invalidate any of the results of this thesis. (See Appendix H). The condition had reached its worst prior to tests on the hydrofoils, and furthermore, comparisons are made against the final evaluation of the total resistance coefficient of the roughened hull. Hence, due consideration for this condition has been exercised.

Turning now to the other curves, it will be noted that Figures X and XI are merely an evaluation of the added resistance that is caused by the support arms of the bow and stern hydrofoil support devices. This evaluation takes account of the roughened condition of the model's bottom as is indicated by the curves shown on the plots. These curves prove that the support arms do result in added resistance, and it would be incorrect to not consider this fact when analyzing the effects due to the hydrofoil alone.

Figures XII, XIII, and XIV could be combined into one single plot, but the result would be a mass confusion of 32 knot range intercept curves. It will be observed that the value of C_T at the 32 knot range for

stated that this condition apparently was typical [illegible]
tions, and hence must exist [illegible] in the [illegible]
within that solution of any point in [illegible]
[illegible]. It is the opinion of the [illegible] that
any [illegible] in [illegible]
[illegible] and does not tend to invalidate any of the
results of this thesis. (See Appendix B). The con-
dition had [illegible] its worst [illegible] in the
[illegible], and furthermore [illegible] are made
against the final evaluation of the total resistance
coefficient of the roughened hulls. Hence, the [illegible]
[illegible] for this condition has been [illegible].

Turning now to the other curves, it will be noted that Figures X and XI are merely an evaluation of the model resistance that is caused by the support arm at the bow and stern [illegible] support devices. This evaluation takes account of the roughened condition of the model's bottom as is indicated by the curves shown on the plots. These curves prove that the support arms do result in some resistance, and it would be incorrect to not consider this fact when analyzing the effects due to the hydrofoil alone.

Figures XII, XIII, and XIV could be combined into one single plot, but the result would be a mass confusion of [illegible] lines [illegible]. It will be observed that the values of C_T at the [illegible] for

any particular condition being considered is the desired information to be gained from all of the curves. Note that each curve has an identifying number which provides a key for establishing what conditions applied for that curve. (See Appendix D).

Figure XV, which shows the effect of longitudinal position on C_T for the 1.0, 1.5, and 2.0 inch foils, must not be considered as being indicative of the best results to be achieved with the stern hydrofoils. The curves on this plot are merely the result of varying one variable while the other two variables are held constant at values which are not necessarily the optimum for them. What is significant is the fact that chord length very definitely does have an effect on the proper positioning of a stern hydrofoil. As will be seen in Figure XVI, when the chord length is decreased, the hydrofoil should be moved forward with respect to the After Perpendicular. Conversely, an increase in chord length requires that the foil be moved further aft. Of some interest in Figure XV is the hump that occurs in the C_T versus Longitudinal Position curve for the 1.0 inch foil. This hump is believed due to the fact that when the 1.0 inch foil is located at 0.15 feet forward of the After Penpendicular it coincides almost exactly with the lowest point in the stern wave hollow. Therefore the local depth of submergence for the foil is not the optimum 1 inch, but is

something less than this. Figure XXI definitely establishes that a submergence depth less than one chord will result in an increased value of C_T, hence this explanation for the hump seems plausible.

With the data gained from Figure XVI as to optimum longitudinal position for the 1.0, 1.5, and 2.0 inch foils it next followed that Figure XVII, C_T versus Hydrofoil Angle of Attack, would indicate two important pieces of information. These are the optimum angle of attack for each foil, and also whether or not any foil when located at its optimum longitudinal position and optimum angle of attack would result in a reduction of the model's C_T at the 32 knot range. As is quite readily seen in Figure XVII neither the 1.0, 1.5, nor 2.0 inch stern hydrofoil succeeded in reducing the model's C_T at the 32 knot range. It is to be remembered that the foils were at their optimum longitudinal positions, and were at either one chord length or at keel depth submergence, which meant they were optimumly located from a submergence standpoint within the imposed limits that were discussed in the <u>PROCEDURE</u>. Therefore, on the basis of Figure XVII it appeared that stern hydrofoils could not effect an improvement in the wave making characteristics of this particular model.

Before terminating this discussion of Figure XVII, a most interesting point must be discussed. This point

is the fact that negative angles of attack for the three stern hydrofoils considered were found to be the optimum. While at first glance this may seem unusual, actually it is entirely to be expected. Figure III shows that this transom-stern model has a pronounced aft cut away area that begins near the aft one third length of the hull. As a consequence, the lines of flow in this aft area will tend to follow the upward sweep of the hull. Therefore, while a negative angle of attack with respect to the water surface might exist, locally the angle of attack was positive due to the direction of flow of the stream lines.

Now it is to be noted in Figure XVII that it was the 2.0 inch stern hydrofoil which resulted in the lowest C_T at its optimum angle of attack. This fact gave an impetus to continue the stern hydrofoil investigations by an analysis of the results which would be caused by the 2.5 and 3.0 inch hydrofoils when they were located at their optimum positions. In order to predict these optimum positions it was therefore necessary to develop Figure XVIII which shows the variations of optimum angle of attack with hydrofoil chord length. Before continuing the discussion of the 2.5 and 3.0 inch foils, note in Figure XVIII that as

of the fact that negative angles of attack for the three inch hydrofoils considered were found to be the optimum. While at first glance this may seem unusual, actually it is entirely to be expected. Figure III shows that this Eastern-Stream model has a pronounced aft cut away area that begins over the aft one third length of the hull. As a consequence, the lines of flow in this aft area will tend to follow the upward sweep of the hull. Therefore, while a negative angle of attack with respect to the water surface might exist, locally the angle of attack was positive due to the direction of flow of the stream lines.

Now it is to be noted in Figure XVII that it was the 2.0 inch chord hydrofoil which resulted in the lowest C_T at its optimum angle of attack. This fact gave an impetus to continue the above hypothetical investigations by an analysis of the results which would be caused by the 1.5 and 1.0 inch hydrofoils when they were located at their optimum positions. In order to predict these optimum positions it was therefore necessary to develop Figure XVIII which shows the variations of optimum angle of attack with hydrofoil chord length. Before continuing the discussion of the 1.5 and 1.0 inch foils, note in Figure XVIII that as

chord length increases the optimum angle of attack changes from negative to positive. This would indicate that the larger foils are influenced by a type of stream line whose path diverges away from the upward sweep of the hull and then tends to become more nearly parallel to the undisturbed water surface. It is to be recalled that Figure XVI indicated that the large foils should be further aft of the A.P., and back in this area the foil will ride in the wake of the model. Figure XXVI showed this area to be quite disturbed by eddies; however, it is relatively level which would indicate that an imaginary laminar stream line in this turbulent area would most certainly not be directed upward as is the case beneath the transom of the model. Hence the indication that large chord length foils should be set at positive attack angles is quite reasonable.

Returning now to the 2.5 and 3.0 inch stern foils, their optimum positions were determined by extrapolation on Figures XVI and XVIII, and Figure XIX shows the C_T versus $V/\sqrt{L}$ characteristics caused by these foils. Also shown for comparison purposes are the same characteristics for the other foils when located at their optimum positions. It is readily apparent that the 2.5 and 3.0 inch foils failed to meet expectations and that the 2.0 inch foil was in reality the foil of optimum chord length.

In Figure XX will be found a plot of stern hydrofoil chord length versus C_T. This curve more clearly establishes the fact that the 2.0 inch chord stern hydrofoil came closest to achieving a reduction in the C_T of the model at the 32 knot range. Furthermore, the curve also shows that the 2.0 inch foil was the only foil to achieve a reduction in wave making resistance. The short dashed lines at each chord length indicate the value of C_T that was to be expected if the model's wetted surface had been increased by an amount equal to that of each foil, and if the resistance caused by the stern hydrofoil support arms was also added to this. (For additional details, see Appendix F.)

The announced intentions of this thesis were to evaluate the effects of stern hydrofoils at both the 32 knot range and the 15 knot range. Following the unsuccessful attempts to reduce C_T in the 32 knot range, it was doubtful whether any improvement could be achieved in the 15 knot range. Figure XX has clearly indicated that the increases in frictional and form drag resistance as a result of the stern foils was in all cases greater than the reduction in wave making resistance. Therefore, since the 15 knot range was characterized by high frictional and low wave making resistance it seemed almost certain that no improvement was possible in the 15 knot range,

by use of stern hydrofoils. In order to prove the point, data was taken to provide the curves of Figure XXI. Only the 1.0 and 3.0 inch hydrofoils were considered, since they would serve to indicate the upper and lower limits of resistance that would result from a complete test of all five foils in the family. These foils were set at their optimum positions as found in the 32 knot range analysis, and as can be seen in Figure XXI no reduction in C_T at the 15 knot range was indicated as being possible.

One final point of discussion with regard to stern hydrofoils is centered upon the effects of submergence depth on the performance of a foil. As was mentioned in the PROCEDURE only the 1.0 inch foil was of small enough chord dimension to permit variation of the depth of submergence. Figure XXII shows the results that were achieved when this foil was tested at greater and less than one chord length depths as compared with the results achieved when set exactly at one chord length depth. As the curves clearly show a submergence greater than one chord length is more harmful than a submergence less than one chord length; additionally, one chord length appears to be the optimum depth of submergence for a hydrofoil to be employed as a wave making reduction device.

B. Bow Hydrofoil Results

As the final phase of this thesis, a limited investigation of results to be achieved with bow hydrofoils was made in order to establish if wave making resistance caused by the fore body was susceptible to reduction. Inasmuch as the 2.0 inch foil had given the best comparative results in the stern hydrofoil investigation, it was decided to use this foil in the bow hydrofoil investigation.

Figure XXIII shows the intercept curves that were used to establish the values of C_T at the 32 knot range for various positions of the bow hydrofoil. A predicted optimum longitudinal position of the hydrofoil was first computed. (See Appendix G.) Thereafter various longitudinal positions of the hydrofoil were examined and curve XXIV was developed to show the effect of variation of the longitudinal position upon C_T. It is interesting to note that the predicted best position was within 0.45 inches of the experimantally determined best position. Of particular significance is the sharp rise in C_T that occurred when the hydrofoil was positioned exactly at the Forward Perpendicular. Reference (9) had established the fact that a hydrofoil moving through water at a submergence depth less than one chord length would produce a surface disturbance immediately above the foil.

Now this very sharp rise in C_T is attributed to the fact that when the 2.0 inch foil was positioned exactly at the Forward Perpendicular it was at a submergence of 1.761 inches which was less than one chord length. Moreover, at this particular position it was immediately beneath the bulbous bow of the model. Accordingly, the effect of the hydrofoil was to cancel some of the beneficial effect achieved by the wave reducing properties of the bulbous bow. This cancellation was thus reflected in an increase in the value of C_T at the 32 knot range.

The angle of attack tests for the 2.0 inch bow hydrofoil, located at its optimum longitudinal position, established the very unexpected fact that the best angle of attack was negative and not positive. (See Figure XXV.) This is described as being unexpected because the optimum longitudinal position was found to be forward of the Forward Pependicular where the lines of flow are not affected in any way by the hull as occurs under the after body. It is clear that the 2.0 inch bow hydrofoil failed to improve the wave making characteristics of the model, and so the negative angle of attack can only be explained by the fact that it undoubtedly caused the least form drag. As will be seen in Figure XXV this optimum angle was only (-)0.65 degrees which is quite small. Reference (11) indicates that the N.A.C.A. foil number 63_3-618 will

produce the least amount of form drag at a negative attack angle of one degree; hence, minimization of form drag required that the hydrofoil be set at a negative angle of attack.

C. Final Point of Discussion

To conclude this discussion attention is once more drawn to Figures XX and XXV. As was previously mentioned, the 2.0 inch stern hydrofoil was the only hydrofoil that achieved a wave making reduction. For all other foils, the fact that the measured values of C_T exceeded the maximum expected increase in C_T at the 32 knot range requires an explanation. (See Figure XX.)

The only logical explanation seems to be that the bow and stern hydrofoils produced a form drag and a surface wave disturbance which caused the increments of added resistance. These increments of added resistance due to form drag and surface wave disturbance were about the same for the 1.0 and 1.5 inch stern foils. However, for the 2.5 and 3.0 inch stern foils these increments tended to increase as chord length increased. The constancy of the increments for the smaller stern foils is explained by the fact that the 1.5 inch foil had greater wave reducing tendencies than the 1.0 inch foil; however,

the 1.5 inch foil also had greater form drag producing tendencies which apparently equalled the wave reducing tendencies. The result was that the 1.5 inch foil's increment remained the same. Now in the case of the 2.5 and 3.0 inch foils, they were carried much too close to the water surface, which meant ever-increasing surface-wave-disturbance tendencies. Additionally, as these foils increased in chord length they also increased in thickness, and consequently there was a progressive increase in form drag. The above, therefore, is proposed as one explanation for the failures of stern hydrofoils to improve C_T at the 32 knot range on this particular model.

V. CONCLUSIONS

The most significant conclusion to be drawn from this investigation is that before applying stern hydrofoils to a hull form a careful evaluation of that form must take place. In general, if the hull form is very fine-lined, and if the stern wave disturbance is very small compared to that of the bow, it is doubtful whether stern hydrofoils can achieve a reduction in wave making resistance. In the model on which Mr. Kozlowski[7] applied a stern hydrofoil, the longitudinal coefficient was 0.639. For the model employed in this investigation, the longitudinal coefficient was 0.572. Hence it is clear that stern hydrofoils are not suitable for application to extremely fine hull forms.

With regard to the use of bow hydrofoils on this particular hull form, it appears on the basis of a very limited investigation that possibly no benefit will result from such use. But this foregoing conclusion is subject to exception, for only one rectangular hydrofoil shape was investigated. Mr. Beal and Mr. Zakay[8] have previously found that the swept back hydrofoil showed more promise than rectangular shaped hydrofoils. Further-

more, the process of a bulbous bow and a hydrofoil acting together, although not actually as one unit, suggests the desirability of further investigation.

The conclusions to be drawn as regards chord length, longitudinal position, angle of attack, and depth of submergence of stern hydrofoils can only be considered as being fully applicable to the hull form under consideration. Since no benefit was achieved by use of stern hydrofoils, the various tests carried out merely served to indicate what was the proper value of the variables so as to attain the least deleterious influence from the foil. However, with this reality in mind, it was found that a foil having a (LBP)/(Chord Length) ratio of 25.99 was best. It is to be recalled that Mr. Kozlowski successfully employed a hydrofoil whose value for that ratio was 24.00.

With respect to longitudinal position of the stern hydrofoil, it was found that the proper position for the hydrofoil of optimum chord length (2 inches in this case) was at a position 1.0115(LBP) aft of the Forward Perpendicular.

As regards angle of attack for the optimum foil, the correct angle is best described by the ratio, (Keel cut away angle)/(hydrofoil angle of attack). This ratio is used because in the area immediately beneath a transom stern, the lines of flow for the water

passing along the hull will follow the general upward sweep of the underbody. Hence, the best angle of attack for a stern hydrofoil will be a function of the upsweep of the hull and the flow lines following this change in form. The local direction of flow thus establishes the proper angle of attack, even though it may be negative with respect to the horizontal. For the model of this investigation, the ratio has been found to be (-)13. The minus sign, of course, indicates that the angle of attack was negative for the reasons given above.

Concerning the optimum depth of submergence, it appears that one chord length is the optimum depth. More harmful effects will result from placing the foil too deep than will result from locating it at less than one chord length in depth.

VI. RECOMMENDATIONS FOR FUTURE RESEARCH

As was evidenced by the data obtained for the 2 inch stern hydrofoil, and also as a result of Mr. Kozlowski's work(7), it has definitely been established that stern hydrofoils will reduce stern wave making resistance. The degree of reduction appears to be a function of the hull form of the vessel being considered.

In order to verify this last statement, it is suggested that the lines for a full bodied ship having the same displacement and wetted surface as the prototype in this investigation be developed. This of course will be a shorter, beamier, and possibly deeper hull form.

After the model for this new form has been built, it is recommended that a hydrofoil from the family tested in this thesis then be attached to the stern of this new model. It is further recommended that the size of the model should be considered very carefully before development of the lines in order to closely approximate the (LBP)/(Chord Length) ratio of 24 to 26.

As a first trial, the selected hydrofoil might be positioned on the basis of the experimental results

given in the CONCLUSIONS section of this thesis.

As a final word of advice, it is recommended that extreme care be exercised in the design of a towing bracket as well as for a support device for the hydrofoil. Any model towed at high speed in the M.I.T. Towing Tank is subject to possible yawing if the towing bracket is even slightly misaligned.

Further, if the hydrofoil is not completely level in the transverse direction, it will act like an airplane wing which has a dihedral angle in one wing but none in the other. The result is that the model is caused to heel because the components of lift are not symmetrical and tend to produce an unbalanced heeling moment.

In conclusion, it is recommended that extreme care be exercised to keep the inside of the model dry while testing. Also, brittle lacquer or enamel type paints should be avoided.

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APPENDIX A

Characteristics of Model DTMB-DD 332 and
Model 17 of Mr. Kozlowski.

APPENDIX A

Characteristics of Model DTMB-DD 332 (ASW-Transom Stern)

Item	Model	Ship
Length between perpendiculars	4.333 ft.	520 ft.
Beam	0.446 ft.	53.5 ft.
Draft	0.147 ft.	17.6 ft.
Displacement	7.63 lb. F.W.	6540 tons S.W.
Wetted Surface	2.028 sq.ft.	29200 sq.ft.
Designed Speed	2.920 knots	32.0 knots

Designed Speed Length Ratio = 1.402

Longitudinal Coefficient = 0.572

$$\frac{\Delta}{\left(\frac{L}{100}\right)^3} = 46.51$$

Scale Ratio = 120

APPENDIX A Con'd

Characteristics of Model 17 (Destroyer) used by Mr. Kozlowski

Item	Model	Ship
Length between perpendiculars	5.5 ft.	369 ft.
Beam	0.604 ft.	40.5 ft.
Draft	0.216 ft.	13.4 ft.
Displacement	21.09 lb.F.W.	2844 Tons S.W.
Wetted Surface		
(a) Naked Model	3.524 sq.ft.	15,860 sq.ft.
(b) Model with Hydrofoil	3.680 sq.ft.	16,564 sq.ft.
Designed Speed	4.26 knots	35 knots

Designed Speed Length Ratio = 1.82

Longitudinal Coefficient = 0.639

$$\frac{\Delta}{\left(\frac{L}{100}\right)^3} = 56.3$$

Scale Ratio = 67.091

APPENDIX B

N.A.C.A. Air Foil Shapes Recommended for Hydro-
foil Research.

APPENDIX B

List of N.A.C.A. Air Foil Shapes Suitable for Use in Hydrofoil Research

The following N.A.C.A. shapes have characteristics closely approximating those of N.A.C.A. foil number 63_3-618. The page number following each foil is the location of data for the foil in N.A.C.A. Report No. 824 of 1945.

1.	N.A.C.A.	4412	p. 141
2.	"	63_2-215	167
3.	"	63_4-421	176
4.	"	64_3-418	194
5.	"	64_3-618	195
6.	"	64_4-421	198
7.	"	65_3-618	225

APPENDIX C

Details of N.A.C.A. Foil No. 63_3-618

(a) Explanation of designation.

(b) Basic offset constants for foil shape.

(c) Location of foil support points.

(d) Use of sandstrips on foils.

APPENDIX C

Details of N.A.C.A. Foil No. 63_3-618.

A. Explanation of Designation 63_3-618

The numbers are treated in the order in which they appear from left to right.

6: This is the series designation.

3: This denotes the chordwise position of minimum pressure in tenths of the chord behind the leading edge for the basic symmetrical section at zero lift.

Subscript 3: A N.A.C.A. identifying number which indicates the low drag range to distinguish the foil from earlier airfoils.

6: This is the design lift coefficient in tenths.

18: These two digits indicate the airfoil thickness in per cent of the chord.

B. Basic Offset Constants Used in Arriving at the Shape of the Foil

First, it is necessary to define two terms.

Mean Line: This is a line which lies midway between the upper and lower surface of the foil. It does not coincide with the chord line unless the foil is a symmetrical shape.

Basic Thickness Form: This is a term used to describe the thickness of the foil at points along the mean line. The longitudinal or x coordinate establishes the position of a point on the mean line. The y coordinate designates the symmetrical thickness about the mean line along a line perpendicular to the mean line. This line passes through the given x coordinate intercept on the mean line.

Meanline Data		Basic Thickness Form Data	
x	y	x	y
0	0	0	0
1.25	0.489	1.25	2.217
2.5	0.958	2.5	3.104
5.0	1.833	5	4.362
7.5	2.625	7.5	5.308
10	3.333	10	6.068
15	4.50	15	7.225
20	5.333	20	8.048
25	5.833	25	8.600
30	6.000	30	8.913
40	5.878	40	8.845
50	5.510	50	7.942
60	4.898	60	6.455
70	4.041	70	4.622
80	2.939	80	2.691
90	1.592	90	0.985
100	0	100	0

The above x and y coordinates are expressed as percentages of the chord.

Additionally:

Leading Edge Radius = 2.12% of chord

Slope of Radius Through Leading Edge = 0.2527% of chord.

The shape of a N.A.C.A. 63_3-618 foil may be seen in Figure V. In the foreground of this figure will be seen an unfinished 1.0 inch chord foil as it is received after cutting in the Sloan Laboratory Machine Shop.

C. Location of Support Points for Hydrofoils

For all foils the support point was located on the mean line at 25% of the chord aft of the leading edge. This position roughly approximates the general longitudinal location of the center of lift as the angle of attack is varied. All longitudinal positions of the foil refer to the location of this support point.

D. Use of Sandstrips on Hydrofoils

The question arose as to the need for sandstrips on the hydrofoils in order to insure turbulent flow conditions around the foil. For tests in the 32 knot range, the local Reynolds number for the 1 inch foil was 7.75 x 10^4. At this particular range of Reynolds number the frictional resistance coefficient for laminar flow is greater than that for turbulent flow. Accordingly, by not using sandstrips and allowing laminar flow on the submerged hydrofoil, the possible beneficial results produced by the hydrofoil are penalized. The result is

a greater percentage amount of resistance caused by friction than would be the case for full sized turbulent conditions. Accordingly, if the hydrofoils did produce beneficial results in the model tests, one would know that even better results were possible in the full size ship where conditions were turbulent and a smaller frictional coefficient existed.

[illegible]

APPENDIX D

Test Data and Calculated Results

TEST NO. 1

Date: 12 February 1954
Temperature of Water: 66°F (The water in the M.I.T. Towing Tank is fresh water)
Purpose of Test: Evaluation of C_T versus $V/\sqrt{L}$ for unsanded, naked hull.
Location of Plot: Figure IX, Curve 1.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F	$V/\sqrt{L}$
1	0.010	0.615	0.006	2.728	0.296
2	0.020	0.770	0.016	4.671	0.370
3	0.030	0.946	0.026	5.035	0.455
4	0.040	1.117	0.035	5.000	0.537
5	0.050	1.270	0.045	4.942	0.610
6	0.060	1.407	0.055	4.904	0.676
7	0.070	1.536	0.065	4.859	0.738
8	0.080	1.651	0.075	4.847	0.793
9	0.090	1.760	0.084	4.822	0.846
10	0.100	1.870	0.094	4.873	0.899
11	0.110	1.962	0.104	4.793	0.943
12	0.120	2.057	0.114	4.776	0.989
13	0.130	2.141	0.124	4.792	1.029
14	0.140	2.227	0.134	4.782	1.070
15	0.150	2.292	0.144	4.849	1.101
16	0.160	2.365	0.154	4.868	1.136
17	0.170	2.425	0.164	4.932	1.165
18	0.180	2.473	0.174	5.029	1.188
19	0.190	2.523	0.184	5.106	1.212
20	0.200	2.568	0.194	5.200	1.234
21	0.210	2.607	0.204	5.304	1.253
22	0.220	2.645	0.214	5.407	1.271
23	0.230	2.682	0.223	5.504	1.289
24	0.280	2.835	0.273	6.032	1.362
25	0.320	2.970	0.313	6.296	1.427

TEST NO. 2

Date: 20 February 1954
Temperature of Water: 66.5°F
Purpose of Test: Completion of the C_T versus $V/\sqrt{L}$ test for unsanded, naked hulls
Location of Plot: Figure IX, Curve 1.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.095	1.818	0.090	4.795	0.874
2	0.100	1.871	0.094	4.776	0.899
3	0.105	1.915	0.099	4.800	0.920
4	0.145	2.274	0.139	4.757	1.093
5	0.150	2.320	0.144	4.738	1.115
6	0.155	2.350	0.149	4.775	1.129
7	0.240	2.710	0.233	5.640	1.302
8	0.250	2.742	0.243	5.745	1.318
9	0.260	2.770	0.253	5.859	1.331
10	0.270	2.794	0.263	5.990	1.343
11	0.290	2.858	0.283	6.160	1.373
12	0.300	2.901	0.293	6.189	1.394
13	0.310	2.920	0.303	6.317	1.403
14	0.320	2.971	0.313	6.297	1.428
15	0.330	2.993	0.323	6.400	1.438
16	0.340	3.033	0.333	6.424	1.458
17	0.350	3.066	0.343	6.575	1.473

TEST NO. 3

Date: 27 February 1954
Temperature of Water: 68.8°F.
Purpose of Test: Evaluation of added resistance resulting from stern hydrofoil support device located at After Perpendicular. Model equipped with sandstrips on bow.
Location of Plots: Runs 1-6, Figure X, curve 2.
Runs 7-16, Figure XI, curve 3.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.040	1.044	0.035	5.784	0.502
2	0.050	1.190	0.045	5.684	0.572
3	0.055	1.260	0.050	5.620	0.606
4	0.060	1.325	0.055	5.588	0.637
5	0.065	1.386	0.060	5.562	0.666
6	0.070	1.448	0.065	5.513	0.696
7	0.270	2.747	0.263	6.220	1.320
8	0.290	2.810	0.283	6.397	1.350
9	0.300	2.838	0.293	6.490	1.364
10	0.310	2.869	0.303	6.567	1.379
11	0.320	2.897	0.313	6.652	1.392
12	0.330	2.926	0.323	6.725	1.406
13	0.340	2.957	0.333	6.788	1.421
14	0.350	2.993	0.343	6.823	1.438
15	0.360	3.028	0.353	6.861	1.455
16	0.370	3.046	0.363	6.973	1.464

TEST NO. 4

Date: 6 March 1954
Temperature of Water: 67°F
Purpose of Test: Evaluation of added resistance due to attaching sandstrips to naked hull.
Location of Plot: Figure IX, curve 4.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.370	3.105	0.363	6.688	1.492
2	0.360	3.065	0.353	6.676	1.473
3	0.350	3.057	0.343	6.520	1.469
4	0.340	3.018	0.333	6.493	1.450
5	0.330	2.995	0.323	6.396	1.439
6	0.320	2.938	0.313	6.447	1.412
7	0.310	2.908	0.303	6.373	1.397
8	0.300	2.880	0.293	6.286	1.384
9	0.290	2.847	0.283	6.213	1.368
10	0.280	2.815	0.273	6.130	1.353
11	0.270	2.782	0.263	6.045	1.337
12	0.260	2.748	0.253	5.960	1.320
13	0.250	2.714	0.243	5.869	1.304
14	0.230	2.646	0.224	5.668	1.272
15	0.340	2.999	0.333	6.576	1.441
16	0.210	2.569	0.204	5.476	1.234
17	0.190	2.482	0.184	5.294	1.193
18	0.170	2.377	0.164	5.146	1.142
19	0.150	2.240	0.144	5.093	1.076
20	0.130	2.081	0.124	5.085	1.000
21	0.110	1.910	0.104	5.074	0.918
22	0.090	1.708	0.085	5.143	0.821
23	0.070	1.488	0.065	5.201	0.715
24	0.050	1.225	0.045	5.338	0.589
25	0.040	1.075	0.035	5.430	0.517
26	0.030	0.910	0.026	5.480	0.437
27	0.020	0.719	0.016	5.415	0.346
28	0.010	0.459	0.006	5.113	0.221

TEST NO. 5

Date: 20 March 1954
Temperature of Water: 61.5°F.
Purpose of Test: Determination of optimum longitudinal position for the 2 inch stern hydrofoil, with $\alpha = +7°$, and h = keel depth, for all runs. Sandstrips on bow. Support device at stern.
Details and Location of Each Plot:
Runs 1-5, for l=0.063 ft. F.A.P., curve 5
Runs 6-10, for l=0.038 ft. A.A.P., curve 6
Runs 11-15, for l=0.163 ft. F.A.P., curve 7
Runs 16-20, for l=0.138 ft. A.A.P., curve 8
Each of the Above Curves will be found in Figure XIV.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.370	2.855	0.363	7.869	1.372
2	0.390	2.911	0.383	7.988	1.399
3	0.400	2.937	0.393	8.050	1.411
4	0.410	2.960	0.403	8.127	1.422
5	0.420	2.990	0.413	8.162	1.437
6	0.420	3.009	0.413	8.058	1.446
7	0.410	2.965	0.403	8.100	1.425
8	0.400	2.948	0.393	7.990	1.417
9	0.390	2.920	0.383	7.939	1.403
10	0.370	2.866	0.363	7.809	1.377
11	0.370	2.848	0.363	7.907	1.369
12	0.390	2.905	0.383	8.023	1.396
13	0.400	2.935	0.393	8.062	1.410
14	0.410	2.961	0.403	8.123	1.423
15	0.420	2.988	0.413	8.173	1.436
16	0.420	2.989	0.413	8.168	1.436
17	0.410	2.963	0.403	8.111	1.424
18	0.400	2.938	0.393	8.047	1.412
19	0.390	2.910	0.383	7.995	1.398
20	0.370	2.855	0.363	7.869	1.372

TEST NO. 6

Date: 21 March 1954

Temperature of Water: 63.5°F.
Purpose of Test: Determination of optimum longitudinal position for the 1.5 inch stern hydrofoil, with α = +7°F, and h = keel depth, for all runs. Sandstrips on bow. Support device at stern.
Details and Location of each Plot:
Runs 1-5, for l=0.063 ft. F.A.P., curve 9
Runs 6-10, for l=0.036 ft. A.A.P., curve 10
Runs 11-15, for l=0.163 ft. F.A.P., curve 11
Runs 16-20, for l=0.136 ft. A.A.P., curve 12
Each of the Above Curves will be found in Figure XIII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.400	2.951	0.393	7.995	1.418
2	0.390	2.920	0.383	7.959	1.403
3	0.370	2.895	0.363	7.675	1.391
4	0.410	2.980	0.403	8.039	1.432
5	0.360	2.835	0.353	7.782	1.362
6	0.360	2.834	0.353	7.786	1.362
7	0.370	2.860	0.363	7.864	1.374
8	0.390	2.915	0.383	7.985	1.401
9	0.400	2.945	0.393	8.028	1.415
10	0.410	2.974	0.403	8.072	1.429
11	0.410	2.975	0.403	8.066	1.430
12	0.400	2.947	0.393	8.015	1.416
13	0.390	2.913	0.383	7.997	1.400
14	0.370	2.857	0.363	7.882	1.373
15	0.360	2.826	0.353	7.832	1.358
16	0.360	2.805	0.353	7.899	1.348
17	0.370	2.832	0.363	7.969	1.361
18	0.390	2.889	0.383	8.083	1.388
19	0.400	2.916	0.393	8.137	1.401
20	0.410	2.944	0.403	8.239	1.415

TEST NO. 7

Date: 24 March 1954
Temperature of Water: 65.8°F.
Purpose of Test: Determination of the optimum angle of attack for the 1.5 inch stern hydrofoil with l=0.05 ft. F.A.P., and h = keel depth, for all runs. Sandstrips on bow. Support device at stern.
Details and Location of Each Plot:
Runs 1-4, for $\alpha = 0°$, curve 13
Runs 5-8, for $\alpha = 3°$, curve 14
Runs 9-11, for $\alpha = 5°$, curve 15
Runs 12-15, for $\alpha = -1.18°$, curve 16
Each of the Above Curves will be found in Figure XIII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.360	2.887	0.353	7.522	1.387
2	0.370	2.915	0.363	7.587	1.401
3	0.390	2.970	0.383	7.706	1.427
4	0.400	3.005	0.393	7.720	1.444
5	0.400	2.972	0.393	7.898	1.428
6	0.390	2.942	0.383	7.857	1.414
7	0.370	2.886	0.363	7.742	1.387
8	0.360	2.858	0.353	7.675	1.373
9	0.360	2.836	0.353	7.795	1.363
10	0.370	2.861	0.363	7.879	1.375
11	0.390	2.919	0.383	7.983	1.403
12	0.400	3.007	0.393	7.710	1.445
13	0.390	2.979	0.383	7.659	1.432
14	0.370	2.925	0.363	7.531	1.406
15	0.360	2.891	0.353	7.501	1.389

TEST NO. 8

Date: 26 March 1954
Temperature of Water: 66°F.
Purpose of Test: Completion of tests for determining the optimum angle of attack for the 1.5 inch stern hydrofoil with l = 0.05 ft. F.A.P. and h = keel depth, for all runs. Sandstrips on bow. Support devide at stern.
Details and Location of Each Plot:
Runs 1-5, for α = -3.18°, curve 17.
Runs 6-9, for α = -5.18°, curve 18.
Each of the Above Curves will be found in Figure XIII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.360	2.895	0.353	7.491	1.391
2	0.370	2.910	0.363	7.621	1.398
3	0.390	2.975	0.383	7.686	1.430
4	0.400	3.003	0.393	7.737	1.443
5	0.370	2.915	0.363	7.594	1.401
6	0.360	2.891	0.353	7.509	1.389
7	0.370	2.913	0.363	7.605	1.400
8	0.390	2.966	0.383	7.734	1.425
9	0.400	2.989	0.393	7.814	1.436

TEST NO. 9

Date: 27 March 1954
Temperature of Water: 66.5°F.
Purpose of Test: A. Completion of optimum angle of attack tests for the 1.5 inch stern hydrofoil, with l = 0.05 ft. F.A.P., α = -2.18°, h = keel depth; see runs 1-4 as listed below.

B. Beginning of optimum longitudinal position tests for the 1.0 inch stern hydrofoil with h = 1 inch submergence, and α = -2.18°; see runs 5-29.

Details and Location of Each Plot: Runs 1-4, for 1.5 inch foil, see A. above, plotted as curve 19 in Figure XIII.

The following runs pertain to the 1.0 inch stern hydrofoil; their curves will be found in Figure XII.

Runs 5-9, for l = 0.15 ft. F.A.P., curve 20
Runs 10-14 for l = 0.25 ft. F.A.P., curve 21
Runs 15-19 for l = 0.35 ft. F.A.P., curve 22
Runs 20-24 for l = 0.425 ft. F.A.P., curve 23
Runs 25-29 for l = 0.150 ft. F.A.P., curve 24

Model equipped with sandstrips on bow, with support device at stern.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.400	3.011	0.393	7.700	1.447
2	0.390	2.976	0.383	7.686	1.430
3	0.370	2.919	0.363	7.577	1.403
4	0.360	2.890	0.353	7.521	1.389
5	0.360	2.895	0.353	7.493	1.391
6	0.370	2.925	0.363	7.454	1.406
7	0.390	2.984	0.383	7.645	1.434
8	0.400	3.012	0.393	7.694	1.447
9	0.380	2.955	0.373	7.592	1.420
10	0.360	2.902	0.353	7.456	1.395

(continued)

TEST NO. 9 (continued)

Date: 27 March 1954

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
11	0.370	2.934	0.363	7.497	1.410
12	0.380	2.962	0.373	7.557	1.423
13	0.390	2.989	0.383	7.618	1.436
14	0.400	3.012	0.393	7.694	1.447
15	0.360	2.900	0.353	7.467	1.393
16	0.370	2.930	0.363	7.517	1.408
17	0.380	2.952	0.373	7.609	1.419
18	0.385	2.974	0.378		1.429
19	0.400	3.012	0.393	7.694	1.447
20	0.360	2.873	0.353	7.609	1.381
21	0.370	2.902	0.363	7.668	1.395
22	0.380	2.935	0.383	7.906	1.410
23	0.390	2.959	0.383	7.776	1.422
24	0.400	2.989	0.393	7.818	1.436
25	0.360	2.898	0.353	7.477	1.393
26	0.370	2.925	0.363	7.545	1.406
27	0.380	2.939	0.373	7.678	1.412
28	0.390	2.981	0.383	7.660	1.432
29	0.400	2.995	0.393	7.784	1.439

TEST NO. 10

Date: 28 March 1954
Temperature of Water: 66.8°F.
Purpose of Test: Completion of optimum longitudinal position tests for the 1.0 inch stern hydrofoil with h = 1 inch submergence, and $\alpha = -2.18°$. Sand strips on bow. Support device at stern.
Details and Location of Each Plot:
Runs 1-5, for l = 0.05 ft. A.A.P., curve 25
Runs 6-10 for l = 0.15 ft. A.A.P., curve 26
Runs 11-15 for l = 0.30 ft. A.A.P., curve 27
Runs 16-19 for l = 0.20 ft. F.A.P., curve 28
Each of the Above Curves will be found in Figure XII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.360	2.899	0.353	7.475	1.393
2	0.370	2.926	0.363	7.543	1.406
3	0.380	2.955	0.373	7.596	1.420
4	0.390	2.990	0.383	7.615	1.437
5	0.400	3.017	0.393	7.670	1.450
6	0.360	2.888	0.353	7.534	1.388
7	0.370	2.915	0.363	7.601	1.401
8	0.380	2.943	0.373	7.659	1.414
9	0.390	2.969	0.383	7.726	1.427
10	0.400	2.994	0.393	7.793	1.439
11	0.360	2.876	0.353	7.595	1.382
12	0.370	2.898	0.363	7.693	1.393
13	0.380	2.925	0.373	7.756	1.406
14	0.390	2.950	0.383	7.828	1.418
15	0.400	2.976	0.393	7.889	1.430
16	0.360	2.917	0.353	7.380	1.402
17	0.370	2.946	0.363	7.438	1.416
18	0.380	2.972	0.373	7.509	1.428
19	0.390	3.002	0.383	7.552	1.443

TEST NO. 11

Date: 29 March 1954
Temperature of Water: 66.8°F.
Purpose of Test: Determination of the optimum angle of attack for the 1.0 inch stern hydrofoil with l = 0.20 ft. F.A.P., and h = 1.0 inch submergence, for all runs. Sand-strips on bow. Support device at stern.
Details and Location of Each Plot:

Runs 1-4, for α = -6.36°, curve 29
Runs 5-8, for α = 0°, curve 30
Runs 9-12, for α = 2°, curve 31
Runs 13-16 for α = 4°, curve 32

Each of the Above Curves will be found in Figure XII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.360	2.889	0.353	7.527	1.388
2	0.370	2.917	0.363	7.590	1.402
3	0.390	2.962	0.383	7.763	1.423
4	0.400	2.993	0.393	7.798	1.438
5	0.360	2.902	0.353	7.458	1.395
6	0.370	2.930	0.363	7.522	1.408
7	0.390	2.980	0.383	7.668	1.432
8	0.400	3.012	0.393	7.697	1.447
9	0.360	2.878	0.353	7.586	1.383
10	0.370	2.898	0.363	7.693	1.393
11	0.390	2.950	0.383	7.828	1.418
12	0.400	2.980	0.393	7.869	1.432
13	0.360	2.835	0.353	7.817	1.362
14	0.370	2.864	0.363	7.886	1.376
15	0.390	2.917	0.383	8.010	1.402
16	0.400	2.940	0.393	8.088	1.413

TEST NO. 12

Date: 2 April 1954

Temperature of Water: 66.5°F.

Purpose of Test: A. Runs 1-5, Re-evaluation of C_T versus $V/\sqrt{L}$ at 32 knot range of model with sandstrips and hydrofoil support device only. The hydrofoil support device is at 0.20 ft. F.A.P.

B. Runs 6-10, Re-evaluation of C_T versus $V/\sqrt{L}$ of model with sandstrips only, at 32 knot range.

C. Runs 11-18, Evaluation of varying the depth of submergence of the 1.0 inch stern hydrofoil. Sandstrips on bow. Support device at stern.

Details and Location of Each Plot:

Runs 1-5, curve 33, Figure XI.

Runs 6-10, curve 34, Figure IX.

Runs 11-14, 1 inch foil at l = 0.20 ft. F.A.P., α = -3.18°, h = keel depth. Curve 35, Figure XXII.

Runs 15-18, 1 inch foil at l = 0.20 ft. F.A.P., α = -3.18°, h = 1.0 inch below water line, i.e., one chord length. Curve 36, Figure XXII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.400	3.110	0.393	7.215	1.494
2	0.330	2.904	0.323	6.811	1.396
3	0.320	2.875	0.313	6.735	1.382
4	0.340	2.927	0.333	6.908	1.407
5	0.350	2.956	0.343	6.967	1.421
6	0.300	2.851	0.293	6.410	1.370
7	0.310	2.881	0.303	6.492	1.384
8	0.320	2.906	0.313	6.590	1.396
9	0.330	2.936	0.323	6.658	1.411
10	0.350	2.992	0.343	6.803	1.438
11	0.350	2.864	0.343	7.440	1.376
12	0.370	2.918	0.363	7.581	1.402
13	0.380	2.940	0.373	7.671	1.413
14	0.390	2.953	0.383	7.809	1.419
15	0.350	2.881	0.343	7.352	1.384
16	0.370	2.942	0.363	7.455	1.414
17	0.380	2.967	0.373	7.532	1.426
18	0.390	2.992	0.383	7.600	1.438

TEST NO. 13

Date: 5 April 1954
Temperature of Water: 67°F.
Purpose of Test: Completion of evaluation of varying the depth of submergence of the 1.0 inch stern hydrofoil. Sandstrips on bow. Support device at stern.
Details and Location of Plot: Runs 1-6, 1.0 inch foil at l = 0.20 ft. F.A.P., α = -3.18°, h = 0.687 inch below water line. Curve 37, Figure XXII.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.350	2.884	0.343	7.342	1.386
2	0.370	2.937	0.363	7.486	1.411
3	0.380	2.963	0.373	7.556	1.424
4	0.390	2.993	0.383	7.602	1.438
5	0.360	2.907	0.353	7.434	1.397
6	0.340	2.850	0.333	7.299	1.370

TEST NO. 14

Date: 10 April 1954
Temperature of Water: 68.5°F.

Purpose of Test:

A. Runs 1-5, Re-evaluation of C_T versus $V/\sqrt{L}$ at the 15 knot range for the sanded model. No hydrofoils or hydrofoil support device are attached to the model.

B. Runs 6-10, Re-evaluation of C_T versus $V/\sqrt{L}$ at the 15 knot range for the sanded model, with stern hydrofoil support device attached at l = 0.20 ft. F.A.P. No hydrofoils attached.

C. Runs 11-15, Evaluation of C_T versus $V/\sqrt{L}$ at the 15 knot range for the 1.0 inch stern hydrofoil located at its optimum position, i.e., l = 0.20 ft. F.A.P., h = 1 inch submergence and $\alpha = -3.18°$.

D. Runs 16-35, Determination of the optimum angle of attack for the 2.0 inch stern hydrofoil with l = 0.05 ft. A.A.P., and h = keel depth, for all runs. Sandstrips on bow, support device at stern.

E. Runs 36-39, Evaluation of C_T versus $V/\sqrt{L}$ at the 32 knot range for the 3.0 inch stern hydrofoil located at its optimum position, i.e., l = 0.175 ft. A.A.P., $\alpha = 3°$ and h = keel depth, for all runs. Sandstrips on bow, support device at stern.

F. Runs 40-44, Evaluation of C_T versus $V/\sqrt{L}$ at the 15 knot range for the 3.0 inch stern hydrofoil located at its optimum position, i.e., l = 0.175 ft. A.A.P., $\alpha = 3°$, and h = keel depth, for all runs. Sandstrips on bow, support device at stern.

TEST NO. 14 (continued)

Date: 10 April 1954

Purpose of Test: G. Runs 45-49, Evaluation of C_T versus $V/\sqrt{L}$ at the 32 knot range for the 3.5 inch stern hydrofoil located at its optimum position, i.e., l = 0.125 ft. A.A.P., $\alpha = 1°$, h = keel depth.

Details and Location of Each Plot:

Runs 1-5, curve 38, Figure IX.
Runs 6-10, curve 39, Figure X.
Runs 11-15, curve 40, Figure XXI.
Runs 16-19, $\alpha = 0°$, curve 41, Figure XIV.
Runs 20-23, $\alpha = 2°$, curve 42, Figure XIV.
Runs 24-27, $\alpha = 5°$, curve 43, Figure XIV.
Runs 28-31, $\alpha = -1.18°$, curve 44, Figure XIV.
Runs 32-35, $\alpha = -3.18°$, curve 45, Figure XIV.
Runs 36-39, curve 46, Figure XIX.
Runs 40-44, curve 47, Figure XXI.
Runs 45-49, curve 48, Figure XIX.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.070	1.316	0.065	6.693	0.632
2	0.075	1.333	0.070	7.015	0.641
3	0.080	1.440	0.075	6.430	0.692
4	0.074	1.373	0.069	6.518	0.660
5	0.078	1.429	0.073	6.355	0.687
6	0.078	1.394	0.073	6.691	0.670
7	0.080	1.421	0.075	6.614	0.683
8	0.075	1.365	0.070	6.691	0.656
9	0.074	1.350	0.069	6.745	0.649
10	0.070	1.301	0.065	6.847	0.625
11	0.080	1.310	0.075	7.795	0.630
12	0.085	1.365	0.080	7.649	0.656
13	0.090	1.418	0.085	7.529	0.681
14	0.095	1.472	0.090	7.390	0.707
15	0.088	1.401	0.083	7.531	0.673

(continued)

TEST NO. 14 (continued)

Date: 10 April 1954

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
16	0.370	2.958	0.363	7.392	1.421
17	0.380	2.983	0.373	7.469	1.434
18	0.360	2.928	0.353	7.338	1.407
19	0.350	2.896	0.343	7.294	1.392
20	0.350	2.875	0.343	7.403	1.382
21	0.360	2.903	0.353	7.470	1.395
22	0.370	2.931	0.363	7.531	1.408
23	0.380	2.963	0.373	7.571	1.424
24	0.350	2.835	0.343	7.613	1.362
25	0.360	2.863	0.353	7.680	1.376
26	0.370	2.893	0.363	7.736	1.390
27	0.380	2.920	0.373	7.798	1.403
28	0.350	2.899	0.343	7.278	1.393
29	0.360	2.928	0.353	7.338	1.407
30	0.370	2.960	0.363	7.382	1.422
31	0.380	2.990	0.373	7.432	1.437
32	0.350	2.891	0.343	7.319	1.389
33	0.360	2.920	0.353	7.380	1.403
34	0.370	2.950	0.363	7.433	1.418
35	0.380	2.982	0.373	7.473	1.433
36	0.350	2.812	0.343	7.740	1.351
37	0.360	2.840	0.353	7.805	1.365
38	0.390	2.923	0.383	7.990	1.405
39	0.410	2.975	0.403	8.115	1.430
40	0.115	1.479	0.110	8.934	0.711
41	0.110	1.429	0.105	9.153	0.687
42	0.113	1.456	0.108	9.037	0.700
43	0.118	1.508	0.112	8.810	0.725
44	0.108	1.404	0.103	9.275	0.675
45	0.380	2.957	0.373	7.600	1.421
46	0.380	2.893	0.353	7.523	1.390
47	0.370	2.923	0.363	7.572	1.405
48	0.390	2.981	0.383	7.681	1.432
49	0.340	2.835	0.333	7.388	1.362

TEST NO. 15

Date: 11 April 1954
Temperature of Water: 68.5°F.

Purpose of Test:

A. Runs 1-16, Determination of optimum longitudinal position for the 2.0 inch bow hydrofoil with $\alpha = 0°$ and h = keel depth, for all runs. Sandstrips on bow. Support device at bow.

B. Runs 17-32, Determination of the optimum angle of attack for the 2.0 inch bow hydrofoil with l = 0.15 ft. F.F.P., h = keel depth, for all runs. Sandstrips on bow. Support device at bow.

C. Runs 33-36, Evaluation of C_T versus $V/\sqrt{L}$ at the 32 knot range for the sanded model, with the bow hydrofoil support device attached at l = 0.15 ft. F.F.P. No hydrofoils attached.

Details and Location of Each Plot:

Runs 1-4, l = 0.20 ft. F.F.P., curve 49.
Runs 5-8, l = 0.30 ft. F.F.P., curve 50.
Runs 9-12, l = 0.10 ft. F.F.P., curve 51.
Runs 13-16, l = at F.P. curve 52.
Runs 17-20, $\alpha = -3.18°$, curve 53.
Runs 21-24, $\alpha = -1.18°$, curve 54.
Runs 25-28, $\alpha = 1°$, curve 55.
Runs 29-32, $\alpha = 3°$, curve 56.

All of the above curves will be found in Figure XXIII.
Runs 33-36, curve 57, Figure XI.

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
1	0.340	2.828	0.333	7.426	1.359
2	0.360	2.888	0.353	7.549	1.388
3	0.380	2.950	0.373	7.639	1.418
4	0.400	3.012	0.393	7.717	1.447
5	0.340	2.812	0.333	7.515	1.351

(continued)

TEST NO. 15 (continued)

Date: 11 April 1954

Run No.	Applied Force (lbs.)	Speed (knots)	Total Resistance (lbs.)	$C_T \times 10^3$ at 70°F.	$V/\sqrt{L}$
6	0.360	2.875	0.353	7.616	1.382
7	0.380	2.937	0.373	7.706	1.411
8	0.400	2.998	0.393	7.789	1.441
9	0.340	2.824	0.333	7.447	1.357
10	0.360	2.888	0.353	7.549	1.388
11	0.380	2.945	0.373	7.664	1.415
12	0.400	3.003	0.393	7.763	1.443
13	0.340	2.720	0.333	8.032	1.307
14	0.360	2.776	0.353	8.172	1.334
15	0.380	2.828	0.373	8.318	1.359
16	0.400	2.882	0.393	8.440	1.385
17	0.340	2.805	0.333	7.551	1.348
18	0.360	2.865	0.353	7.669	1.377
19	0.380	2.920	0.373	7.800	1.403
20	0.400	2.977	0.393	7.903	1.431
21	0.340	2.827	0.333	7.430	1.358
22	0.360	2.889	0.353	7.542	1.388
23	0.380	2.952	0.373	7.628	1.418
24	0.400	3.011	0.393	7.723	1.447
25	0.340	2.808	0.333	7.535	1.349
26	0.360	2.871	0.353	7.638	1.380
27	0.380	2.930	0.373	7.743	1.408
28	0.400	2.991	0.393	7.826	1.437
29	0.340	2.744	0.333	7.889	1.319
30	0.360	2.802	0.353	8.023	1.346
31	0.380	2.865	0.373	8.104	1.377
32	0.400	2.923	0.393	8.201	1.405
33	0.320	2.877	0.313	6.743	1.382
34	0.340	2.932	0.333	6.902	1.409
35	0.360	2.995	0.353	7.008	1.439
36	0.350	2.965	0.343	6.952	1.425

APPENDIX E

Sample Calculations

APPENDIX E

Sample Calculations

Model DTMB-DD 332

Consider Run 1 of Test 1, conducted on 12 Feb. 1954:

Model Length, $L = 4.333$ ft.

Wetted Surface, $S = 2.028$ sq.ft.

Water Temperature $= 66°F.$

Fresh Water Density, $\rho = 1.9371$ slugs/ft.^{3}

Fresh Water Kinematic Viscosity, $v = 1.1133 \times 10^{-5}$ ft.^{2}/sec.

Applied Force 0.0100 lbs.

Speed 0.615 knots or 1.038 ft./sec.

*Pulley Friction Corresponding to Speed 0.0041 lbs.

* The pulley friction is read from a calibration chart at the M.I.T. Towing Tank. It is the friction arising from the 5 lb. static tension in the towing cable.

1) Calculation of model total resistance coefficient at testing temperature

Force acting on the model = (Applied Force)-(Pulley Friction)

$R_T = 0.0100 - 0.0041 = 0.0059$ lb.

$$C = \frac{R_{T_m}}{\frac{1}{2}\rho S V^2} = \frac{0.0059}{\frac{1}{2}(1.9371)(2.028)(1.038)^2} = 2.786 \times 10^{-3} \text{ at } 66°F.$$

2) <u>Correction of model total resistance coefficient to standard temperature of 70°F.</u>

$$\text{Reynold's number at test temperature} = \frac{VL}{\nu} = \frac{1.038 \times 4.333}{1.1133 \times 10^{-5}}$$

$$= 4.042 \times 10^{5}$$

$$\text{Reynold's number at 70°F.} = \frac{VL}{\nu} = \frac{1.038 \times 4.333}{1.0552 \times 10^{-5}}$$

$$= 4.265 \times 10^{5}$$

Using Schoenherr's formulation for frictional resistance coefficient as tabulated for varying Reynold's number in reference (12), we obtain:

at $R_e = 4.042 \times 10^5$, $C_{F_m} = 5.283 \times 10^{-3}$

at $R_e = 4.265 \times 10^5$, $C_{F_m} = 5.225 \times 10^{-3}$

Correction to $C_T = (5.225 - 5.283) \times 10^{-3} = (-)\ 0.058 \times 10^{-3}$

Finally, at 70°F:

$$C_T = (2.786 \times 10^{-3}) - (0.058 \times 10^{-3}) = 2.728 \times 10^{-3}$$

3) <u>Speed length ratio for run</u>

$$\text{Speed length ratio} = \frac{V}{\sqrt{L}} = \frac{0.615}{\sqrt{4.333}} = 0.296$$

4) Discussion of wetted surface used in Calculations

Throughout the calculations the value of wetted surface used was always that of the model only, not the model plus that of any attached hydrofoil. As a result, the values of C_T obtained are all higher than would have been the case if the added wetted surface of the foils had been included.

This action is justified on these grounds. The foil is not normally considered part of the model. Hence, if the calculations show that a value of C_T is obtained which is less than the value of C_T without the foil, it is a positive indication that the reduction was due entirely to the hydrofoil. The attempt, therefore, is to keep model and hydrofoil separate and distinct in the calculations so as to be able to point toward any improvement as being due solely to the added presence of the hydrofoil. There is, accordingly, a common basis for direct comparison of total resistance coefficient with and without hydrofoils. In reference (5) will be found additional discussion of this point.

APPENDIX F

Expected Increase in C_T at 32 Knot Range Due to Hydrofoil Wetted Surface

APPENDIX F

Expected Increase in C_T at 32 Knot Range Due to Hydrofoil Wetted Surface

As was mentioned in Appendix E, Sample Calculations, the additional wetted surface of the hydrofoils was not added to that of the model when calculating the values of C_T for the various runs.

Now the results of the stern hydrofoil analysis indicate that none of the five hydrofoils resulted in a C_T at the 32 knot range which was lower than the value of C_T to be expected without the presence of hydrofoils. Accordingly, it is not possible to evaluate the wave reducing effects of the hydrofoils unless we first know what was the effect of the frictional resistance caused by the hydrofoil wetted surface.

The following calculations were therefore made to evaluate these added frictional resistance effects.

C_T of banded model (no stern foil support device)

at 32 knot range = 6.620×10^{-3}

Added Increment to C_T caused by stern foil support

device = 0.248×10^{-3}

Span of Foils = 5.330 inches

Model Wetted Surface = 2.028 sq. ft.

Foil Wetted Surface = (Span of Foil) x (Wetted Perimeter)

$$\text{Percent Increase in Wetted Surface} = \frac{\text{Foil Wetted Surface}}{\text{Model Wetted Surface}} \times 100$$

Expected C_T due to Added Wetted Surface

$$= \left(1 + \frac{\%\text{Increase}}{100}\right)(6.620 \times 10^{-3})$$

The figures in the far right column are plotted as dashes in Figure XX.

Chord Length (inches)	Wetted Peri-meter (inches)	Foil Wetted Surface sq. in.	Foil Wetted Surface sq. ft.	Percent Increase in Wetted Surface	Expected C_T due to Added Wetted Surface	Expected C_T plus ΔC_T due to Support Device
1.0	2.01	10.71	0.0744	3.670	6.870×10^{-3}	7.118×10^{-3}
1.5	3.15	16.78	0.1164	5.735	6.990×10^{-3}	7.238×10^{-3}
2.0	4.22	22.84	0.1587	7.810	7.130×10^{-3}	7.378×10^{-3}
2.5	5.25	27.98	0.1942	9.570	7.240×10^{-3}	7.488×10^{-3}
3.0	6.27	33.45	0.2322	11.440	7.570×10^{-3}	7.818×10^{-3}

APPENDIX G

Prediction of Optimum Longitudinal Position for 2 inch Bow Hydrofoil at 2.920 Knots

APPENDIX G

Prediction of Optimum Longitudinal Position for 2 inch Bow Hydrofoil at 2.920 Knots

By a series of observations of the transverse bow wave profile, it was established that the crest of the first bow wave occurred at a point 12.00 inches aft of the Forward Perpendicular. Now previous investigations on bow hydrofoils indicated that the hydrofoil should be located one quarter wave length forward of the first bow crest.

Following reference (2) the expressions for wave length are:

$$\lambda = 0.557\, L\left(\frac{V}{L}\right)^2$$

$$\lambda = 0.557\, V^2 = 0.557(2.920 \times 1.689)^2$$

$$\lambda = 4.74 \text{ ft.}$$

Then $\frac{\lambda}{4} = \frac{4.74}{4} = 1.185$ ft. = 14.25 inches

Finally, recommended position of bow hydrofoil was found to be:

Best Position = 14.25 - 12.00 = 2.25 in. forward of the forward perpendicular.

By experiment, the best position was established as being 1.80 inches forward of the Forward Perpendicular, therefore:

Error in Prediction = 2.25 - 1.80 = 0.45 inch

Considering that visual observation was employed to establish the position of the first bow crest, this small error is quite acceptable in making a first approximation to the proper location.

APPENDIX H

Estimate of the Magnitude of Errors

APPENDIX H

Estimate of the Magnitude of Errors

There were five experimentally controlled or measured variables in this thesis. They are listed below and for each is quoted an estimate of the possible error that may have occurred in their measurement:

Towing Force	$\pm$ 0.0001 lb.
Towing Velocity	$\pm$ 0.001 knot
Hydrofoil Longitudinal Position	$\pm$ 0.002 ft.
Hydrofoil Angle of Attack	$\pm$ 0.25 degree
Hydrofoil Depth of Submergence	$\pm$ 0.002 ft.

The error introduced by the cracking of the model's bottom paint is not readily estimated in the manner shown above. This fact lessens the quantitative value of the results; however, the qualitative results suffer absolutely no depreciation because of this situation. The significant results of this thesis are qualitative in nature and accordingly their accuracy is a function of the thoroughness of experimental investigation. By thoroughness is meant a rigorous search into all the facets that influence the performance of a hydrofoil. It is on this basis that the thesis must be objectively viewed.

Thesis
V37 Venning 28816

The effect of a hydro-
foil at the stern of a
destroyer type vessel
upon its performance in
still water.

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